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Faculty of Mechanical Engineering and Naval Architecture

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Sveučilište u Zagrebu

Fakultet strojarstva i brodogradnje

Tomislav Martinec

MODEL PROCESA OBRADE INFORMACIJA I INTERAKCIJA U TIMSKOM RAZVOJU TEHNIČKIH SUSTAVA

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Mentor:
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CONTENTS

ABSTRACT

Teamwork is often regarded as a critical operation element of many development organisations, whereas an efficient team-based approach to engineering design activities is a prerequisite for the success of technical systems development projects. Design team members thus need assistance in the form of methods and tools that will facilitate collaboration during team design activities, inasmuch as researchers and project managers require support in developing and prescribing the most appropriate and efficient methods and tools for the particular design tasks.

The research reported in the thesis aims at improving the understanding of designing in teams, primarily in the stage of conceptual design and from the perspective of information processing. A more specific research aim has been formed as follows: to review, develop and test models of team design activity in the development of technical systems, which will build on information processing and interaction appearing in team design activities in the conceptual design stage of the development. The main purpose of these models is to enhance decision-making and planning of technical systems development, by enabling both capturing and generation of data sets that reflect process patterns distinctive for specific team compositions and working processes.

A state-transition-based theoretical and mathematical models have been developed and used to experimentally investigate the patterns of design operations during two types of team conceptual design activities – ideation and concept review – as well as two types of engineering design projects – adaptive and innovative. The presented work builds on the perception of design problems as ill-defined and implies that conceptual design activities involve the simultaneous development of problems and solutions through the usage of three distinctive design operations: analysis, synthesis, and evaluation. The three design operations have been defined as fine-grain design steps performed by design teams when exploring the content of both the problem and the solution dimensions of the design space. Moreover, design operations have been conceptualised as transitions between states of the explored design space, thus providing a basis for the state-transition model.

The developed models and the accompanying computational tool fulfilled the purpose of supporting research activity. The results of the protocol analysis and computational simulation studies indicate that the model can be used to identify, analyse and simulate process patterns such as sequences of design operations which are distinctive for specific working processes, such as divergent and convergent team conceptual design activities, as well as for a systematic approach to conceptual design. The experimental findings which could have been compared to the insight from the available literature have been found aligned with the current understanding of designing in teams. The main advantage of the proposed state-transition models is its ability to map various sequences of ASE design operations which emerge during team design activity. Based on the listed findings, it can be argued that the developed state-transition model provides more flexibility when it comes to capturing and comparing the patterns of ASE design operations in the problem and the solution space and offers the potential of improving the understanding of the design process through either experimental or computational studies of team conceptual design activity.

Keywords:

Engineering design process; Teamwork; Information processing; Technical systems development; Conceptual design; State-transition model; Ideation activity; Concept review activity

PROŠIRENI SAŽETAK

Timski rad ključan je element djelovanja gotovo svake organizacije, a učinkovit timski pristup razvojnim aktivnostima jedan je od preduvjeta za uspjeh inovativnih razvojnih projekata. Inovacije nisu specifično vezane samo za izvanredne pojedince već su i doprinos svih ljudi u organizaciji i njihovih zajedničkih aktivnosti. To su potvrdila i istraživanja posvećena formalnim procesima razvoja i nastanka inovacija te njihovom doprinosu uspješnom razvoju novih proizvoda, gdje su proučavanjem najboljih primjera iz prakse definirane smjernice koje je potrebno uključiti u razvojne procese organizacije kako bi se potaknula inovativnost. Uz to, u literaturi je primjetan značajan porast interesa za proučavanje ponašanja inženjera u postojećim procesima i timskim aktivnostima kao što su generiranje ideja, donošenje odluka, rješavanje problema ili pregled konstrukcije.

Istraživanja također pokazuju da još uvijek postoji potreba da se članovima razvojnih timova osigura bolja metodološka podrška i podrška u alatima za koncipiranje i konstruiranje tijekom timskih aktivnosti razvoja tehničkih sustava, a voditeljima projekata alati i metode uz pomoć kojih će se lakše nositi s izazovima koji proizlaze iz kompleksnosti upravljanja timskim radom. Kako bi se to omogućilo, potrebno je razviti formalne modele obrade informacija i interakcija za uobičajene timske aktivnosti u kontekstu razvoja tehničkih sustava. Implementacijom takvih modela u simulacijama timskog rada moguće je generirati skupove podataka potrebne za analizu utjecaja promjena u kompoziciji timova i načinu izvođenja radnih procesa, kao i donošenja odluka pri realizaciji razvojnih projekata.

Cilj je istraživanja osmisliti, formulirati i testirati teoretske i matematičke modele aktivnosti timskog rada u razvoju tehničkih sustava. Istraživanjem se modeliraju procesi obrade informacija i interakcije tijekom timskih aktivnosti. Svrha modela i njihove primjene u eksperimentalnim studijama jest prikupljanje i generiranje skupova podataka relevantnih za analizu obrazaca obrade informacija za različite kompozicije timova i različite radne procese, a koji se mogu koristiti za donošenje odluka pri planiranju i upravljanju razvojnim projektima.

Predloženim istraživanjem verificira se hipoteza da modeliranje i simulacija obrade informacija i interakcija pojedinaca koji sudjeluju u izvođenju timskih aktivnosti omogućuje razumijevanje značajki inovativnih i adaptivnih projekata razvoja tehničkih sustava te time unaprjeđuje planiranje i upravljanje razvojnim projektima.

Metodologija

Istraživanje je metodološki utemeljeno na općoj metodologiji istraživanja u znanosti o konstruiranju te je provedeno u četiri osnovna koraka: preliminarno istraživanje (raščišćavanje zahtjeva na istraživanje), pregled literature (deskriptivno istraživanje I), razvoj teoretskog i matematičkog modela (preskriptivno istraživanje) te provedba eksperimentalnih studija i validacije modela (deskriptivno istraživanje II). Preliminarno istraživanje uključuje pregled postojeće znanstvene i stručne literature unutar područja istraživanja s ciljem inicijalnog opisa postojeće situacije, željenih rezultata te definiranja osnovnih pretpostavki. Definirani su ciljevi, hipoteza i doprinosi istraživanja. Pregledom literature dan je uvid u vrste postojećih modela razvojnih procesa, s posebnim naglaskom na aspekte dekompozicije, obrade informacija i vrste razvojnih projekata. Pregled je uključio modele različitih razina granuliranosti, od modela koji opisuju faze razvoja novih proizvoda do modela timskih aktivnosti koji opisuju korake obrade informacija i interakciju članova tima. Ishod toga koraka jest formulacija istraživačkih pitanja, čime je usmjeren daljnji tijek istraživanja. Razvijena su dva modela. Teoretski model kao dio teoretskog okvira razvijen je na temelju saznanja iz pregleda literature. Drugi, matematički model kreiran je na temelju statističke analize podataka prikupljenih prvom eksperimentalnom studijom. Uz modele su razvijene pripadajuće vizualizacije procesa obrade informacija te računalni alat za simulaciju procesa koncipiranja proizvoda. Eksperimentalne studije provedene su primjenom razvijenih modela u svrhu analize i generiranja podataka relevantnih za procesuiranje informacija u timskim aktivnostima razvoja tehničkih sustava. Rasprava o rezultatima eksperimentalnih studija ujedno je i evaluacija razvijenih modela, posebice u odnosu na formulirana istraživačka pitanja te prema kriterijima postavljenih ciljeva i hipoteze istraživanja.

Teoretske osnove

Preliminarnim pregledom literature istraživanje je fokusirano na timske aktivnosti u fazi koncipiranja proizvoda, gdje tijekom razvoja tehničkih sustava postoji najveća potreba za timskim radom. Za dekompoziciju i modeliranje procesa obrade informacija odabrana je paradigma operacija konstruiranja. Operacije konstruiranja osnovni su mehanizmi obrade informacija kojima se članovi tima koriste kako bi manipulirali sadržaj dviju dimenzija prostora konstruiranja – prostora problema i prostora rješenja.

Formulirane su definicije triju temeljnih operacija konstruiranja: analize, sinteze i evaluacije. Timovi analiziraju kako bi unaprijedili razumijevanje pojedinih konstrukcijskih entiteta u istraženom prostoru konstruiranja. Analizom prostora problema raste razumijevanje potreba, zahtjeva i ograničenja dok se analizom potreba rješenja povećava razumijevanje ideja, koncepata i koncepcijskih alternativa. Nadalje, timovi sintetiziraju kako bi stvorili nove entitete u prostoru konstruiranja. Sintezom rješenja nastaju novi entiteti, ideje i rješenja za zadane probleme dok sintezom problema nastaju entiteti koji opisuju nove potrebe, zahtjeve i ograničenja. Naposljetku, evaluacijom se ocjenjuje korisnost pojedinih entiteta u istraženom prostoru konstruiranja. Za razliku od analize i sinteze, evaluacija uključuje i entitet kriterija, tj. evaluacijom problema i rješenja određuje se korisnost pripadajućih entiteta prema kriteriju formuliranog entiteta u prostoru problema.

Tri temeljne operacije u prostoru konstruiranja objedinjene su u teoretski model prijelaza stanja, kao tranzicije između stanja razvijanog tehničkog sustava, odnosno stanja procesa konstruiranja. Tako koncipiran model omogućuje preslikavanje i analizu udjela operacija konstruiranja, njihovih sekvenci i vjerojatnosti prijelaza iz jedne operacije u drugu tijekom timskih razvojnih aktivnosti. Uz model prijelaza stanja razvijene su i pripadajuće vizualizacije udjela operacija konstruiranja te su definirane varijable i mjere za analizu procesa pomoću eksperimentalnih studija.

Eksperimentalna studija analize protokola

Testiranje teoretskog modela i pripadajućih vizualizacija provedeno je eksperimentalnim studijama. Prva studija provedena je korištenjem analize protokola, a s ciljem identifikacije obrazaca analize, sinteze i evaluacije u prostoru problema i rješenja za dvije različite vrste timskih aktivnosti u konceptualnoj fazi razvoja tehničkih sustava – generiranja ideja i pregleda koncepata. Analiza protokola provedena je za četiri razvojna tima sastavljenih od studenata viših godina strojarstva. Svaki je tim sudjelovao u jednoj aktivnosti generiranja ideja i jednoj aktivnosti pregleda razvijenih koncepata. Proces obrade informacija analiziran je metrikama i vizualizacijama predloženim u okviru teoretskih osnova modela prijelaza stanja.

Primjena teoretskog modela omogućila je identifikaciju obrazaca obrade informacija i interakcija karakterističnih za dvije analizirane aktivnosti, poput divergentnih ciklusa sinteze problema i rješenja tijekom aktivnosti generiranja ideja ili konvergentnih ciklusa analize i evaluacije rješenja za vrijeme aktivnosti pregleda koncepata. Nadalje, primjena modela omogućila je identifikaciju obrazaca koji su bili učestali u obje aktivnosti, poput obrazaca analize, sinteze i evaluacije rješenja te primjene sinteze kao sredstva za prebacivanje iz prostora problema u prostor rješenja i obratno. Potvrđeno je da se odmicanjem faze koncipiranja smanjuje udio operacija konstruiranja u prostoru problema.

Rezultati prve eksperimentalne studije također otkrivaju da timovi na sličan način pristupaju istraživanju prostora problema i rješenja, koristeći se sličnim sekvencama analize, sinteze i evaluacije. Posebno je zanimljivo da ni proces generiranja ideja ni proces pregleda koncepata ne održavaju mikroobrasce analiza – sinteza – evaluacija ili sinteza – analiza – evaluacija, na kojima se temelje neki od modela aktivnosti konstruiranja razmatranih pregledom literature.

Matematički model i računalne eksperimentalne studije

Rezultati i saznanja o obrascima obrade informacija iz prve eksperimentalne studije iskorišteni su za razvoj matematičkog modela. Identificirane su i statistički modelirane veze između udjela i sekvenci operacija konstruiranja. Te su veze, vodeći računa o teoretskim osnovama prijelaza stanja, objedinjene i formalizirane unutar matematičkog modela. Validacija matematičkog modela provedena je repliciranjem rezultata prve eksperimentalne studije (analize protokola). Matematički je model zatim računalno implementiran simulatorom aktivnosti obrade informacija i interakcija u konceptualnoj fazi razvoja tehničkih sustava te su razvijeni novi eksperimenti s ciljem istraživanja obrazaca obrade informacija u inovativnim i adaptivnim razvojnim projektima. Postavke simulacija inovativnih i adaptivnih projekata definirane su na temelju saznanja proizašlih iz pregleda literature.

Niz simulacija adaptivnih i inovativnih projekata omogućio je prikupljanje veće količine podataka o udjelima, redoslijedu i vjerojatnostima primjene operacija konstruiranja u različitim stadijima faze koncipiranja tehničkih sustava. Identificirani su prijelazi stanja karakteristični za dvije vrste projekata, poput konvergentnih ciklusa analize i evaluacije te divergentnih ciklusa sinteze i evaluacije unutar i između prostora problema i rješenja. Nadalje, takvi se prijelazi stanja mogu direktno povezati s koevolucijom prostora problema i rješenja, odnosno epizodama u procesu gdje istraživanje jedne dimenzije prostora konstruiranja izaziva stvaranje novih entiteta u drugoj dimenziji. Više potencijalnih epizoda koevolucije identificirano je za inovativne projekte. S druge strane, u simulacijama procesa adaptivnih projekata uočena je viša razina sistematičnosti, ponajviše u obliku dobro uočljivih konvergentnih i divergentnih stadija konceptualne faze. Formulirana je tvrdnja da su sistematičnost i epizode koevolucije usko povezani s dekompozicijom zadanog konstrukcijskog problema u potprobleme, ali i s neizvjesnošću u planiranju sljedećih koraka procesa razvoja. Adaptivne projekte karakteriziraju niža razina neizvjesnosti i eksplicitna dekompozicija problema na početku konceptualne faze, a inovativne projekte visoka razina neizvjesnosti i implicitna dekompozicija problema.

Vrednovanje istraživanja

Vrednovanje teoretskog i matematičkog modela, kao i podataka prikupljenih analizom protokola i računalnim simulacijama provedeno je raspravom kojom se adresiraju hipoteza, ciljevi i istraživačka pitanja. Rasprava se također oslanja na saznanja iz dostupne literature.

Razvijeni teoretski i računalni modeli te popratne vizualizacije ispunili su svrhu podrške istraživanju timskih aktivnosti u razvoju tehničkih sustava. Rezultati eksperimentalnih studija ukazuju da se modeli mogu koristiti za identifikaciju, analizu i simulaciju obrazaca operacija konstruiranja, poput sekvenci analize, sinteze i evaluacije u prostorima problema i rješenja, a koji su karakteristični za različite razvojne procese, poput divergentnih i konvergentnih timskih aktivnosti te sistematičnog pristupa konceptualnoj fazi razvoja tehničkih sustava. Rezultati analize protokola i računalnih simulacija u skladu su s trenutnim saznanjima u području znanosti o konstruiranju. Štoviše, u usporedbi s postojećim modelima, razvijeni teoretski i matematički modeli, koji se koriste paradigmom prijelaza stanja, nude veću fleksibilnost preslikavanja obrazaca operacija konstruiranja i time unaprjeđuju razumijevanje timskog konstruiranja.

Razvijene vizualizacije prijelaza stanja na tri načina dodatno proširuju razumijevanje identificiranih obrazaca. Prvo, kao svojevrsni sažetak svih prijelaza između operacija konstruiranja unutar i između prostora problema i prostora rješenja, koji odražava frekventnost prijelaza iz jedne operacije konstruiranja u drugu. Drugo, vizualizacije se mogu koristiti kao predlošci za preslikavanje i prikaz uobičajenih obrazaca operacija konstruiranja, ali i obrazaca koji su specifični za pojedine timske aktivnosti u konceptualnoj fazi razvoja tehničkih sustava. Treće, vizualizacije promjene udjela operacija konstruiranja tijekom timskih aktivnosti omogućuju intuitivnu analizu, usporedbu i karakterizaciju procesa konstruiranja za različite timove te mogu pomoći u analizi pojava poput iteracije, neizvjesnosti, istraživanja prostora konstruiranja i sistematičnog pristupa konstruiranju.

Na temelju vrednovanja istraživanja naglašena su tri osnovna aspekta znanstvenog doprinosa. Prvi aspekt obuhvaća razvoj teoretskog modela procesa obrade informacija te interakcija između pojedinaca u timskim aktivnostima razvoja tehničkih sustava te niz novih saznanja o timskim aktivnostima dobivenih primjenom teoretskog modela i paradigme prijelaza stanja za analizu protokola aktivnosti generiranja ideja i pregleda koncepata. Drugi aspekt uključuje pripadajuće originalne načine vizualizacije udjela i uzoraka tranzicija među analizom, sintezom i evaluacijom u prostoru problema i rješenja za timske aktivnosti u razvoju proizvoda. Treći aspekt znanstvenog doprinosa obuhvaća razvoj matematičkog modela i računalnog alata za simulaciju timskih aktivnosti temeljem predloženog teoretskog modela, u svrhu boljeg razumijevanja, planiranja i upravljanja razvojnim projektima, kao i stvaranja novih saznanja o timskom radu u konceptualnoj fazi adaptivnih i inovativnih projekata razvoja tehničkih sustava.

Ključne riječi:

proces konstruiranja; timski rad; procesuiranje informacija; razvoj tehničkih sustava; koncipiranje; model prijelaza stanja; aktivnost generiranja ideja; aktivnost pregleda koncepata

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

AI	-	Artificial Intelligence
ASE	-	Analysis, Synthesis and Evaluation
BAH	-	Booz Allen Hamilton
DDP	-	Design and Development Process
DfX	-	Design for X (Design for Excellence)
DRM	-	Design Research Methodology
EDR	-	Experimental Design Research
FBS	-	Function-Behaviour-Structure
IMoD	-	Integrated Model of Designing
IPD	-	Integrated Product Development
IPS	-	Information Processing System
NPD	-	New Product Development
O	-	Other-related protocol code
PA	-	Problem analysis design operation
PDMA	-	Product Development and Management Association
PE	-	Problem evaluation design operation
PRO	-	Problem-related design operation
PROC	-	Process-related protocol code
PS	-	Problem synthesis design operation
R&D	-	Research and Development
SA	-	Solution analysis design operation
SE	-	Solution evaluation design operation
SOL	-	Solution-related design operation
SS	-	Solution synthesis design operation

Symbols

$\boldsymbol{n}$	-	Total number of design operation instances in a protocol string
$\boldsymbol{n}_{i}$	-	Number of instances of design operation *i*
$\boldsymbol{p}_{i}$	-	Proportion of design operation *i*
$\boldsymbol{R}$	-	Maximum vector length in ASE proportion visualisation
$\boldsymbol{r}$	-	Vector length in ASE proportion visualisation
$\boldsymbol{\delta}$	-	Vector direction angle in ASE proportion visualisation
κ_{a}	-	Event alignment kappa value

1. INTRODUCTION

This introductory chapter outlines the research goal and clarifies its scope in the context of engineering design research. The reader is introduced with the motivation for the conducted research and is provided with a brief overview of the aims, hypothesis, methodologies and the expected contribution driving the work reported in the thesis.

Innovative product development is a critical activity of contemporary product development organisations [1], [2]. Although both the older [3] and the more recent [4] studies have pointed out different types of innovation and different meanings it can have to the stakeholders involved, it is generally agreed that development organisations cannot realise or retain long-term global competitiveness without successfully and repetitively introducing new and innovative products. Over the years, the research efforts (reported mainly within the domain of management research) attempted to identify critical success factors in product development and provided numerous best practice guidelines based on studies of highly innovative organisations across the industry (see, e.g. [5], [6], [7], [8], [9] for more details on the new product development (NPD) best practice studies). Among other things, the studies have broken a common misconception that innovativeness is specifically related only to exceptional individuals, and revealed that, in the ever increasing competitive and interdisciplinary environment, innovation is primarily a contribution of groups of people within the organisation and a result of their joint activity [10], [11] – teams and teamwork [12].

Within the domain of engineering design, which is at the very core of technical systems development, team collaboration turned up to be essential when no single actor has all the time, knowledge, skills or inspiration needed to realise a particular design task [13], [14], [15]. In addition, teamwork has provided many advantages over individual work and has been related to different desirable outcomes such as improved problem solving and product quality, and the reduction of development time and costs [16], [17]. Consequently, being able to work in a team is perceived as one of the core design competencies [18], whereas the engineering design education increasingly encompasses skills such as communication and teamwork, in order to prepare design students for the creative design tasks that emerge in the real-world, professional product development context [19], [20], [21].

Due to the initial individualistic focus, most of what has been known about the engineering design process has resulted from studies of individual designers [22]. Although the number of studies aimed at understanding designing in teams is continuously increasing [23], the proportion of research on design teamwork remains marginal when compared to studies that examine designing with an individualistic focus [24]. While team design activities are potentially the most creative, vibrant and dynamic from the designers' point of view [25], there still remain aspects of team designing that are less understood by the researchers (i.e. the research questions formulated in Chapter 2), thus leaving open calls for both theoretical and experimental research that will frame the comprehensive understanding of teamwork in design.

Therefore, the motivation for conducting the here presented research stems primarily from the need for developing, adapting and upgrading the design process models for the team design activities, thus providing a foundation for building a better understanding of teamwork in engineering design. The motivation founds primarily on a presumption that there exist regularities in designing that transcend any individuals involved in the process [26], [27]. As shown hereafter, the potential benefits of modelling the "designerly" behaviour in team design activity are, at least, twofold.

Firstly, a better understanding is seen as a prerequisite for the development of **better methodological and computational support for design team work**. Namely, given that the fundamental goal of design research is often expressed as improving the design in practice, it is not surprising that its efforts resulted predominantly in an exceedingly large amount of different design methods and tools, rather than providing better understanding and comprehensive models of design [28]. For example, while the efforts of computer-supported collaborative environments could have indeed facilitated design teamwork [29], most of the developed means of support remained at a theoretical level, whereas only a few were implemented in practice [30]. The lack of adequate computer support tools in design practice has been particularly evident in the conceptual design stage of product development [31], [32], [33] during the critical activities such as ideation [34] and design review [35]. Moreover, the tools for collaborative design may fail in supporting effective communication of ideas and information, primarily due to the insufficient exploration of information flows in design teams [15]. It is agreed that the development of support that is intended to improve the design process is likely to be far more efficient and effective if different aspects of designing are better understood [30], [36]. Proper models of the actual design processes have thus become essential for understanding designers' information processing and interaction, as well as developing tools that could assist collaborative designing [15], [28], specifically, design teams in formulating design problems and providing solutions to these problems.

Secondly, an eventual sufficient understanding of interactions and information processing in engineering design teams is expected to **facilitate design team formation and management**. Since teams in product development are usually project based [11], it is not uncommon for members of design teams to meet for the first time when the project starts [37] and produce one-time outputs only [38]. Design teams are formed by project managers and can drag members from different disciplines, based on their expertise and ability to contribute to a particular project, whereas some members work on the project until it is completed, and some join for shorter periods [38]. Hence, it is argued that a better understanding of the effects of design team composition on the design process and design outcomes facilitates the construction and management of effective teams [39]. However, when it comes to forming project-based teams, many selection strategies may assist, but none has emerged as a consistent predictor of effectiveness [40].

For this reason, team formation represents a significant challenge for project managers, as they try to select optimal team memberships and distribute the work activities. Depending on the product's novelty level (often described using terms categorised as original/innovative, adaptive/redesign, variant/configuration, and incremental/routine) [41], [42], different types of design work is expected to be in team's focus [43]. Thus, traditional engineering design might require engineers to solve complex engineering problems with specifications already set and baseline product predetermined [44], while the development of innovative consumer products requires precise identification of users' needs [45]. The understanding team information processing and gaining insight into actions and interactions in project-based design teams facing different types of product development projects is thus important for both researchers and practitioners within the domains of design and product development.

The ability to combine experimental research on the nature of team information processing (e.g. [46], [47], [48]) with the advances in information technologies has opened a space for utilising computer-supported simulations of teamwork as complementary tools for research and management. Although mathematical and computational modelling are currently not fully exploited for design process simulation, they exhibit a high potential for the investigation of fine-grain models of engineering design activity [49]. In this way, the two outlined benefits would intertwine, given that the better understanding of team information processing and interaction helps design researchers not only to better support design teamwork but also to conduct analyses of various design process scenarios, whose insights can then be employed by project managers when forming design teams or allocating resources.

1.1. Research focus, aim and hypothesis

The acts related to designing represent a set of complex, multi-layered phenomena [30], [50], [51], while the product development organisations can be seen as complex-socio technical systems [52]. Therefore, any study of teamwork in design must acknowledge that because of the large number of variables involved and due to the multifaceted nature of the design process [46], [53], only some aspects of designing can be addressed at a time. For example, recent studies in the engineering design domain have investigated team design processes through the lens of design thinking and cognition [54], [55], [56], [57], communication [58], [59], [60], creativity [61], [62], learning [13], [63], [64], systematic approaches to solving a problem [65], [66] as opposed to the co-evolutionary design progression [67], and more. Additionally, insights on human behaviour from domains such as psychology, management and education, are continuously being incorporated in order to yield the most relevant results. Ideally, studies of different aspects of teamwork (within and outside the engineering design domain) should, in the manner of a jigsaw puzzle, be compatible and make up a comprehensive description of team design activities.

The phenomenon of interest in this thesis is the observable information processing performed by the members of a design team, whereas the aspects such as cognition, learning, creativity and personal characteristics of team members are not directly in focus. Information processing is here interpreted as a process-oriented paradigm [68], which accounts for any manipulation of the design content (design information) aimed at providing a solution to a particular design problem. Such highly abstract interpretation aligns with the definitions of engineering design that focus on information and it's conversion or transformation [69], [70], e.g. *"Engineering design is a process performed by humans aided by technical means through which information in the form of requirements is converted into information in the form of descriptions of technical systems, such that technical systems meet the needs of mankind"* [71] or *"Engineering design is the process of converting an idea or market need into the detailed information from which a product or technical system can be produced"* [72]. Similar views on information processing can be applied to any type of problem-solving activity in general [41].

As it is the case with the design process, the decomposition of team information processing (in its broadest sense) within the engineering design literature is variegated and depends highly on the phenomena of research interest. Detailed descriptions of the actual mechanisms of information processing are thus introduced later in the thesis.

Three fundamental reasons for focusing primarily on the information processing phenomenon in order to describe the team design activity can be outlined:

- **Design information processing exhibits regularities.** It has been argued that engineering design can be modelled as an information processing activity, where each step in the process involves design team identifying information that defines a particular sub-problem and then use knowledge, skills and tools to process the information into a state that represents a selected sub-solution [73], [74], [75]. Hence, the execution of information processing acts, such as analysis, synthesis and evaluation of design information, can be seen as a dominant mode of operation of design teams throughout the design process stages [76], [77]. Given the previously introduced conjecture that there exist regularities in designing, information processing is here proposed as a proxy for identifying such regularities. It is thus argued that if the regularities are captured within a model of information processing in design teamwork, that model can be used to describe other phenomena of interest in design research. For example, studies have shown that patterns in information processing activity can reflect phenomena such as fixation, inspiration and creativity [78] or the difference between experts and novice designers [79], [80].
- **Methods for studying information processing reached maturity.** The claim applies particularly for the protocol analysis, a frequently employed process-oriented analysis method which is largely based on the information processing perspective of the design process [81]. Protocol studies have been conducted to gain an understanding of human ways of designing, whereas the resulting protocols of the design process have been widely used to record designers' step-by-step information processing [82], [83]. Information processing paradigm and the verbal protocol analysis method pioneered by Ericsson and Simon [84], have been present within a vast number of engineering design studies for decades, and have as such developed scientific validity and maturity. Their establishment has also been supported by the ever-increasing capability, efficiency and affordability of data capturing and analysis tools needed to perform experimental studies of information processing in design (audio-video hardware and software) [85].
- **Information processing perspective is applicable to the development of computational design support tools.** Within the information processing paradigm, it is assumed that human problem solver together with the task environment and the explored

problem/solution space represent an information processing system (IPS) [77], [86]. Given the premise that IPS-like exploration is a valid basis for computer-based design support [87] and that such support must be integrated within the streams of information processing within the design process [82], it can be argued that an information processing model of design teamwork could provide a foundation for the development of computational tools that can support team design activity. Such argumentation for the compatibility of information processing theories and computational models is already well accepted in design research, and is acknowledged to form a basis for the support of design practice, theory and education [88], as well as the simulation of design teamwork [89] and artificial intelligence (AI) driven designing [77], [90].

Furthermore, due to the diversity of activities within the engineering design process and the many stages it iterates through [49], [91], it is difficult to isolate and model any one type of team design activity that would adequately summarise the complete scope of teamwork in the development of technical systems. Therefore, the here presented work will focus mainly, but not exclusively, on team activities within the context of the conceptual design stage of technical system development. The following rationale can be provided for such a narrowing:

– **Team design activities are conducted primarily during the conceptual design stage.** The potential for harnessing the advantages of team designing prevails primarily within the conceptual design stage of product development, where designers transform the initial, often ill-defined formulation of a design problem is into a clear description of a concept solution, by reducing the unknown and assuring that the subsequent stages are mainly technical in nature [50], [92]. The conceptual design stage makes the greatest demands on designers and offers the most scope for striking improvements [93]. A teamwork approach to framing design problems and developing solutions to these problems is believed to be the driver of creativity and innovativeness in the early product development stages [67]. Hence, not only does the majority of engineering designers in modern industrial practice work as part of a team [94], [95] but the creative conceptual design tasks such as idea generation or concept selection, are often performed exclusively as team activities [61], [96]. It is thus not surprising that a large portion of experimental design research on team behaviour in the last decades has been related directly to the conceptual design stage [23].
– **Conceptual design stage encompasses critical design information processing.** Although this early part of the design process is relatively inexpensive and involves

relatively small groups of people, it incorporates large amounts of information handling [32] and furthermost important [93], but often ad hoc decision-making [97], which together significantly impact the subsequent development stages. Most of the information communicated by designers during conceptual design is verbal [50], [98], occasionally backed up by visual representations as to facilitate shared understanding [99]. Such distinctive nature of information processing, which is specific for conceptualisation when compared to the later stages such as detailing and testing, without doubt, contributes to the previously mentioned lack of adequate support in the form of computational tools for the conceptual design activities [31], [32], [33], [34], [35]. Capturing and modelling information processing during team conceptual designing is argued to be the first step towards the development of computational support tools suitable for information-handling and decision-making throughout the conceptual design stage.

Taking into account the information processing perspective in focus, and based on the outlined lack of understanding and support for team activities in engineering design (particularly within the conceptual design stage), the aims and hypothesis of the research can be summarised as follows:

Research aims: The principal aim of the research is to review, develop and test models of team design activity in the development of technical systems. Given the outlined research focus, the models will build on information processing and interactions of engineering designers during team design activities, particularly within the conceptual design stage of product development. The purpose of the developed models and their application in experimental studies of team designing is to enable both capturing and generation of data sets relevant for the analysis of patterns distinctive for in team composition and working processes, thus enhancing decision-making in planning and management of development projects.

Hypothesis: The proposed research will verify the hypothesis that the modelling and simulation of information processing and interactions of individuals that perform teamwork activities, enable understanding of the features of innovative and adaptive technical systems development and thus facilitate research, planning and management of development projects.

1.2. Research methodology

In general, the aim of research in engineering design science is to formulate and evaluate models and theories on the phenomenon of design and development of technical systems, based on which the strategies, procedures, methods, techniques and tools can be developed to improve practical knowledge, project management and education [30]. Developing models of design and their implementation within computational tools is a very complex task that requires integration of multiple approaches and disciplines [100], especially in engineering design as well as management research concerning NPD. Two ends of the spectrum of design research knowledge can be highlighted: practical and theory knowledge [101]. Methodologically, the two corresponding strands of design research result in the development of understanding and the development of support [30]. Yet both the understanding and the support are needed to make the design process more effective and efficient.

The appropriate interplay between prescriptive and descriptive approaches needed for conducting the here presented research has been found within the Design Research Methodology (DRM) [30] – a general and increasingly spread research methodology in design science. Moreover, aside from the support in the form of the DRM methodology, the research has also been guided by the principles of Experimental Design Research (EDR) [102] and the principles for the construction of design science [70].

Although the presentation of the stages is sequential, the conducted research work requires iteration (similar to designing) and parallel execution of stages (particularly in the case of model development and experimental studies). This particular research project and its main focus can be described as that of Type 4 in DRM [30]. It is characterised by the literature review-based Research Clarification and Descriptive Study I stages, followed by an iterative cycle of model development (Prescriptive Study) and experimental research (Descriptive Study II), as shown in Figure 1.1. The resulting research methodology consists of four main stages, which can be described as follows:

1) **Research clarification:** This stage fully corresponds to the first stage of the DRM methodology. Just as in product development, a need for conducting the (research) work must have been identified and well interpreted. The clarification includes forming the line of argumentations from the existing situation to the research goal [30] (as presented so far in this introductory chapter). The stage resulted in an overall research plan which contains the description of the research problem, the focus, aims and hypothesis, relevant research areas to be reviewed, the research methodology, the expected contribution and the schedule. The structured research process (methodology) also implies the embracing of acknowledged scientific principles and methods [70].

2) **Literature review:** Once the research scope has been clearly defined, it was possible to constrain the body of literature needed to gain an understanding of the investigated phenomena. The review of the specific body of literature corresponds to the second stage of the DRM methodology – Descriptive Study I. The selected literature sources must have been sufficient to describe the existing situation (the state of the art) and point out the aspects of design that are most suitable to address in order to improve the situation, but also to identify the knowledge relevant for evaluation of the potentially improved situation [30]. As such, the literature review has focused primarily on the topics of the design process and activity decomposition, teamwork in design and experimental investigation of team designing. Moreover, as highlighted previously, the review included also the sources of knowledge in domains outside of engineering design and product development, thus satisfying the principle of maximally utilising knowledge contained in all knowledge areas [70].

3) **Model development:** At this point, the research approach has switched from descriptive to prescriptive. Model development has been conducted in two separate steps. First, the literature review knowledge has been synthesised within a single theoretical framework – a theoretical model of information processing and interactions in teams developing technical systems. This theory-based model has been intended primarily to frame the investigation of information processing patterns observed in team design activities. Based on the guidelines for evaluation of experimental design studies and metrics, reported as part of the EDR [103], the theoretical foundation must be encompassed by identification, definition and measures of variables which are key to the observed phenomena. Testing of the theoretical model in a protocol analysis study and obtaining experimental data enabled further prescriptive developments. Namely, a mathematical model has been developed by means of statistical modelling and by following the principles of developing scientific models from experimental design research [27]. The mathematical model has then been utilised to simulate team activities throughout the conceptual design stage, thus gaining valuable insights for both design teamwork research and management. Within the DRM, the stage of support (model) development is named the Prescriptive Study. It utilises the knowledge collected throughout the available literature to conceptualise the intended support (model) and uses the understanding gained via additional experimental studies to deliver the final support (models, visualisations and simulation tools) [30]. The two prescriptive steps have maximised the application of graphical representations along

with verbal explanations and mathematical-symbolic relationships, as a suitable language of design engineers [70].

4) **Experimental studies and model evaluation:** This final descriptive stage has focused on testing and validating the developed models, as well as expanding the descriptive knowledge on designing in teams (the fourth stage of DRM – the Descriptive Study II). Since it was intertwined with the model development stage, the descriptive study has been conducted in two separate steps – each implying experimental design research. In the first experimental study, the theoretical model was employed for protocol analysis of team conceptual design activity. The protocol analysis study was built on the guidelines for human-focused research in engineering design, whereas the applied protocol coding scheme has been developed to reflect the elements and granularity of the model's theoretical foundation [102]. In addition to expanding the knowledge on team conceptual design activity, the first experimental study provided data for the development of the mathematical model. After the mathematical model has been formulated, computational simulation studies of specific setups of team conceptual design activities were conducted. The computationally-generated experimental datasets were subject to a new analysis, aimed particularly at generating new descriptive insights on designing in teams as well as validating the utility of the model. Validation here implies primarily the comparison with the insight reported in the available literature.

1.3. Scientific contribution

Valkenburg and Dorst stated that *"in order to improve team designing, we have to understand it, in order to understand we must be able to describe it"* [104]. The expected contribution of the research reported in this PhD thesis is concerned with the latter two – providing a valid description of team design activity and utilising the developed description in order to improve the understanding of team designing. These two aspects of scientific contribution are manifested through:

- Development of theoretical and mathematical models of information processing and interactions between individuals during team activities in the development of technical systems.
- Development of a teamwork activity simulation tool based on the proposed models, which can be used for better understanding, planning, management and support of team design activities.

1.4. Thesis structure

The thesis is divided into eight chapters that, to some extent, follow the previously described stages of the research methodology. The thesis structure is shown in Figure 1.1.

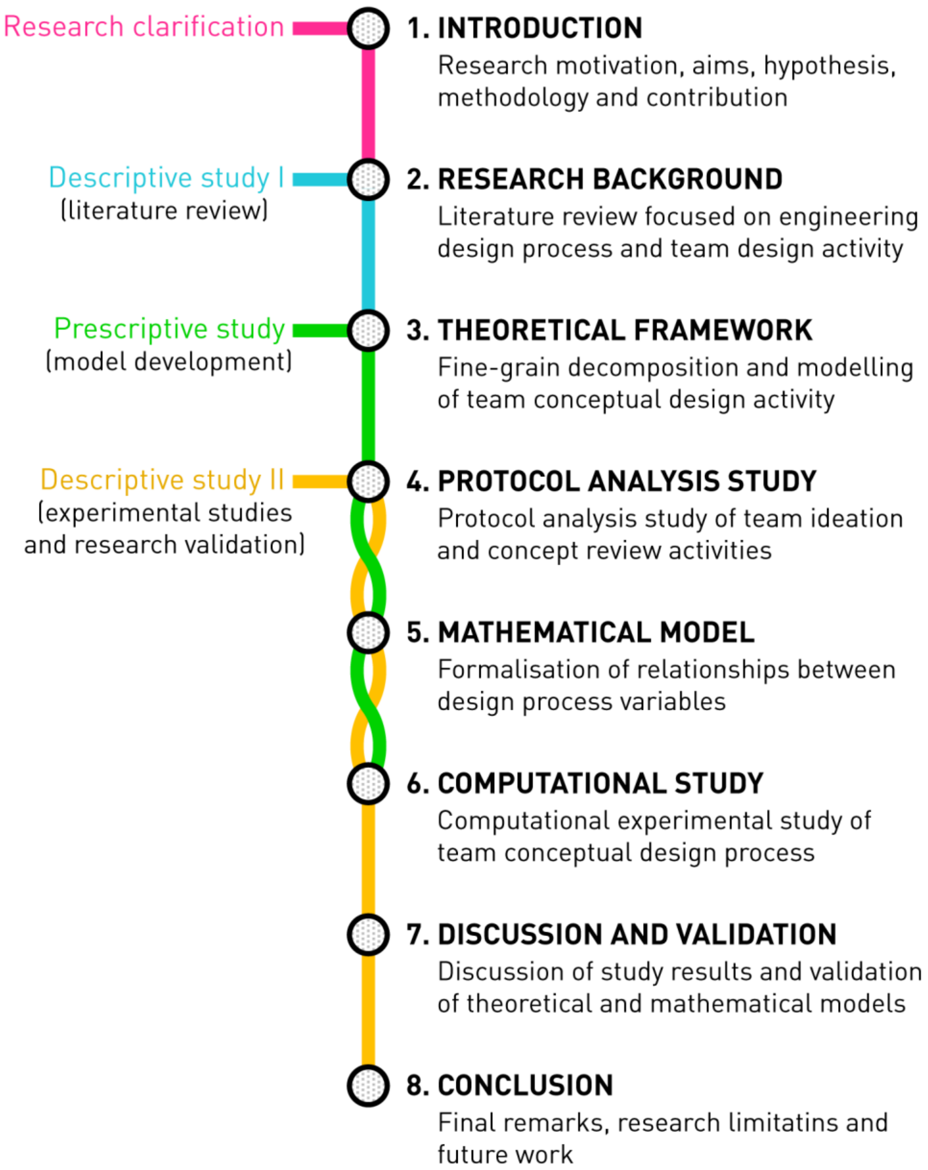

Figure 1.1 Structure of thesis chapters and corresponding stages of DRM

Chapter 1 introduces the research motivation and provides a brief overview of research aims and hypothesis, the adopted methodologies and the expected contribution driving the reported work. As such, the introductory chapter encompasses the outputs of the DRM's Research Clarification stage.

Chapter 2 summarises the literature review study and defines the research gaps. The literature review is reported in three sections, each aimed at presenting insights of a particular research area – the overall product development process as portrayed in the management research, the technical systems development stage of product development as prescribed in engineering design textbooks, and the team design activity as described by the recent efforts within the design research literature. The fourth section outlines the identified state-of-the-art research gaps and formulates research questions that will guide the following work. The research background chapter corresponds to the Descriptive Study I stage.

Chapter 3 concerns the theoretical foundation of the thesis. There, the selected literature review insights are synthesised into a theoretical framework for the fine-grain decomposition and modelling of team conceptual design activity. Three fundamental design information processes are defined and associated with changing the state of the problem- and solution-related information entities. The resulting theoretical model and the associated visualisations are proposed as a means of investigating the proportions and sequences of design information operations during different types of team conceptual design activities. Regarding DRM, the theoretical framework chapter represents the outputs of the first, yet an essential step of the Prescriptive Study stage.

The developed theoretical model has been applied for the analysis of experimental sessions of two types of team conceptual design activity – ideation and concept review. The experimental investigation has been conducted in the form of a protocol analysis study and is reported in Chapter 4. The results include descriptive and inferential statistical analysis of proportions and sequences of design information operations observed during the two types of conceptual design activities. By reporting on the information processing patterns that are both common and distinctive for the two activities, the chapter corresponds to the first step in the Descriptive Study II stage.

Chapter 5 reports on the second part of the Prescriptive Study, where the data obtained in the protocol analysis study is used to develop a mathematical model. Regression modelling has been used to formalise the relationships in-between the variables that describe the proportions and sequences of design information operations. In addition, a computational tool with two main purposes has been developed: to facilitate the testing of the formalised regression models' predictive power, and to enable simulation of additional data concerning information processing and interaction patterns.

Following the development of the mathematical model and the associated simulation tool, Chapter 6 reports on the second (computational) experimental study. Namely, the mathematical model has been utilised as a means for a computational generation of data on information processing and interaction characteristic for the conceptual design stage of innovative and adaptive design projects. The simulated data has again been analysed in regard to information processing patterns, thus expanding the outputs of Descriptive Study II.

The model and the data gathered via protocol analysis and computational studies are discussed and validated in Chapter 7. The chapter addresses the hypothesis and research questions raised in the first two chapters. Furthermore, the insights from the available literature have been used to discuss the protocol analysis and computational study results, along with the reflection on the theoretical and mathematical models and their potential application in research and management of engineering design projects.

In Chapter 8, the Descriptive Study II is concluded by reflecting on the expected scientific contributions, discussing the research limitations and providing guidelines for conducting future research regarding modelling of information processing and interactions in teams developing technical systems.

2. RESEARCH BACKGROUND

The second chapter summarises the Descriptive Study I. It reports on the most relevant literature concerning decomposition and categorisation of engineering design processes and team design activities in the context of product development. Particular attention is given to insights associated with team information processing in different stages and activities of technical system development. Finally, gaps in the literature regarding the introduced research hypothesis are discussed at the end of the chapter.

The term "technical systems" represents all types of man-made artefacts, including technical products and processes, which are subject of the collection of activities performed by engineers as part of the engineering design process [105]. Just as technical systems fulfil user's needs by transforming objects from one state into another (desired) state, the engineering design is used to convert a need for a technical system into the detailed information from which the technical system can be produced [72]. Hence, engineering designers together with design methods and tools must produce various effects to achieve an appropriate flow of information that will result in a sufficient elaboration of the technical system.

The engineering design process, which is here referred to as transformation of engineering design information, is characterised by its layered and multifaceted nature. Namely, the engineering design process consists of a number of short-term activities which can be further decomposed into flows of steps taken by the designers. On the other hand, engineering design represents only a fragment of an overall information transformation system – the product (technical system) development process. Any attempt to model the development process has embodied a selective viewpoint, and the state-of-the-art understanding can only be found by combining models and findings associated with different scopes of the development [49]. Namely, given the hypothesis proposed in the introduction, the primary focus of here presented research is the team design activity. However, to be able to model team designing at various stages of the (conceptual) design and development of technical systems, and within projects of different levels of novelty (e.g. innovative and adaptive), the contextual overview of the overall product development process and engineering design has been made. Therefore, the literature review aims to introduce team design activity within a broader context of engineering design and product development.

The relevant literature review findings are presented in three parts, that is, on three levels of detail the development of technical systems can be investigated. The three levels correspond to the macro-, meso- and micro-level as defined by Wynn et al. [49]. At the macro level, the models focus on project structures and the context of the design process. Meso-level concerns the end-to-end flows of tasks, whereas micro-level models focus on fine-granular process steps, typically during individual or small group situations [49]. As shown in Figure 2.1, the three sections of literature review present the move from an overall NPD macro perspective (Section 2.1) to the meso-level investigation of the engineering design process (Section 2.2), and towards the micro descriptions of team design activity (Section 2.3). Centric to this approach is not only gathering of knowledge which can be synthesised within the model of team design activity, but also the identification of gaps in the literature and formulation of research questions that would guide the following research steps (Section 2.4).

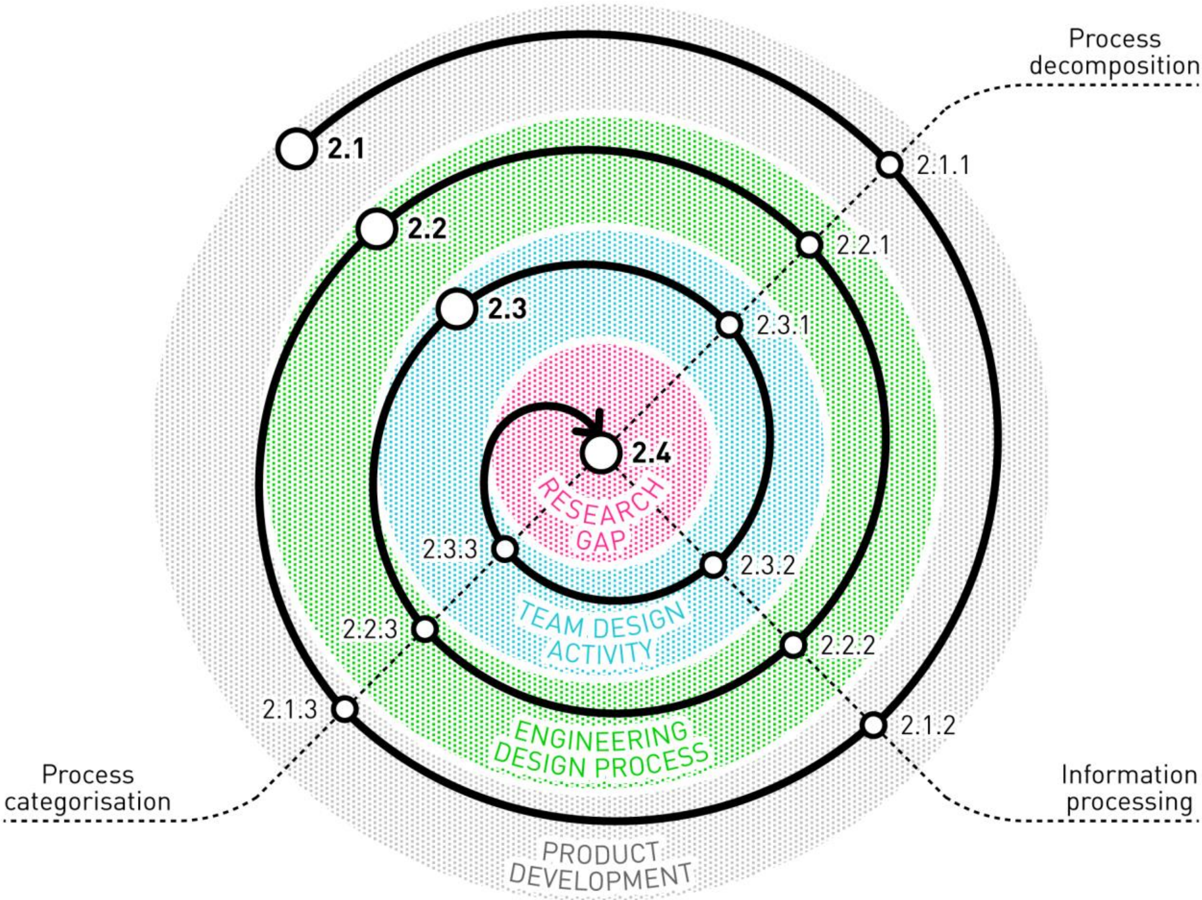

Figure 2.1 Overview of research background sections and their relation to product development, engineering design and team design activity processes, as well as decomposition, categorisation and information processing aspects of analysis

Moving towards the centre of the circle increases the granularity of analysis, but also represents a change from prescriptive (procedural) models of product development to descriptive (abstract and theoretical) models of design. Additionally, moving around the circle represents addressing different aspects of analysis, from decomposing the process into smaller fragments and investigating the nature of information-processing within these fragments, to categorising different types of projects, processes and activities appearing at that particular level of analysis.

2.1. Product development: The big picture

The research on process-related practices in product development organisations is extensive and encompasses a wide range of studies that separate “the best from the rest” and prescribe an integrated approach for executing product development activities. The resulting body of literature originates mainly from the management literature (where the product development process is usually regarded as NPD); hence the focus is not solely on the engineering process but instead considers research, strategy and marketing activities along with the development of products. The research concerning NPD is here briefly presented to provide an understanding of the context in which engineering design takes part. Besides outlining the core product development stages and activities, the review is focused on identifying general types of information processing appearing throughout the stages as well as development variations discussed in the literature.

The reviewed prescriptive models represent only a fragment of what is available in the product development literature. In order to place the development of technical systems in the context of the overall product development process, the review has been constrained mainly to the stage-based depictions of the NPD. For a more comprehensive review of the special-purpose prescriptive models of the product development process, please consult recent literature studies on the topic of design and development processes (DDP) [49], [106], [107].

2.1.1. Decomposition of NPD process

The macro-level product development process in product development organisations is often represented using the stage-based models, which are easy to interpret and apply [108]. A stage is a subdivision of the product development process that relates to the state of the product under development. The low granularity of process representation is what makes stage-based models applicable in different environments and in different types of product development projects.

One of the commonly adopted models is the stage-gate system by Cooper [109], [110], which is both a process structuring approach and the representation of linear progress within stages of NPD. The main purpose of the stage-gate system is to give a prescriptive “idea-to-launch process” for new (innovative) products, following a set of best practice guidelines and including gate checkpoints to ensure quality. Depending on the company or division, stage-gate systems involve up to seven stages. Development, which includes the design of the product, is in the middle of the process, preceded by detailed investigation (building a business case) and followed by testing and validation [109]. Initially, Cooper and Kleinschmidt developed a general “skeleton” of the NPD process [5] in order to explore the best practice and proficiency of NPD activities. The study compared successful versus unsuccessful projects, and showed significant impact of the frequency and proficiency of design activities on the project outcomes, making them one of the key activities in the NPD process [5]. The authors additionally recommended to focus on the initial screening and market analyses in order to attain innovation success [5]. A recent adaptation of the stage-gate system by Schmidt et al. [8] compressed the typical stage-gate process into four stages: opportunity detection, preliminary marketing and technical assessment, development and testing (which includes design), and commercialisation. While the first stage-gate models represented NPD as a linear process, the newer generations of the acknowledged concurrent (parallel) execution of the development activities [110]. Nevertheless, Hart and Baker argue that concurrency requires functional separation of tasks, whereas it is the results of these tasks that converge at decision points [111], [112].

Many best practice studies were carried out under the auspices of the Product Development and Management Association (PDMA). These reports are the continuation of the broad-based studies conducted by Booz Allen Hamilton (BAH) in 1968 and 1982 [113]. They described the development stage as an iterative translation of product ideas into product offerings [114]. Once the BAH studies were no longer accurate reflections of the state of the field, Page [6] conducted a new cross-sectional study sponsored by PDMA, which reported on the status of NPD in the 1990s. Unlike the studies mentioned above, Page gave more attention to designing and highlighted the early design activities related to idea generation and concept development. According to Page, these activities are followed by the product development stage, which he characterised as pure technical work aimed at converting the concepts into working products [6]. In this way, the conceptual design stage, which includes creative tasks such as brainstorming and preliminary team discussions about the product’s design, has been separated from the development and testing stage, which are more technical. The supporting data confirms the presence and importance of the conceptual and product development activities in practice (more than 75% of respondents included these specific activities in their NPD processes). Moreover, the study revealed an increasing interest for multidisciplinary teams as organisational structures in NPD [6]. The following PDMA studies, conducted by Griffin [7] and Barczak et al. [9] have retained a similar frame of process activities while updating the trends and benchmarking the best practices. A somewhat detailed process decomposition can be found in a study by Song and Montoya-Weiss [115], who selected the most frequent NPD activities based on the discussions within articles, pilot studies and in-depth case studies. Activities which are primarily related to design include: expanding ideas into conceptual solutions; evaluating development and manufacturing feasibility; determining product features (functions) and form; conducting engineering, technical and manufacturing assessments; prototype development; and final product design [115]. The most recent findings on NPD practices can be found in the PDMA Handbook of New Product Development [116] and within the continuously updated editions of Crawford and Di Benedetto's New Product Management [12], who provide a more extensive and granular decomposition of the NPD process from the management point of view.

The prescriptive approaches within the design research domain have embraced the above mentioned stages in order to describe the interaction between the design process and the NPD context within which a design is delivered [49]. These approaches focus on integrating design activities with marketing and business aspects of NPD. For example, the Technological innovation methodology by Archer [117] decomposes NPD into an extensive list of tasks, making conceptual design activities part of the research stage, where the market insights and technical feasibility of the concept solution evolve together. The Total Design by Pugh [118] provides a systematic methodology for the better integration of engineers and designers within the overall product development process, from market research to commercialisation. Similar aims can be found within the two notable engineering design textbooks: Integrated Product Development (IPD) by Andreasen and Hein [119] and Product Design and Development (PDD) by Ulrich and Eppinger [120]. Both represents the NPD process as concurrent flow of marketing-, design- and production-related activities. In IPD, the designers are involved in determining the type of product, defining the working principles, preliminary and final design, as well as potential adaptation based on sales and production. PDD puts additional emphasis on the strategic planning and technical/market screening activities, as well as evaluation activities throughout the NPD process (e.g. concept evaluation and user testing studies).

Design research approaches usually adopt the textbook NPD processes. Nevertheless, there have been attempts to revisit and expand the NPD practices from the design perspective. Fairlie-Clarke and Muller have thus developed a generic model of product development activities consisting of 18 generic elements [112]. Each of these generic elements comprises of a set of activities, which can be mapped onto the custom processes found in both the NPD literature and practice. Despite the sequential representation, authors emphasise that the NPD process does not imply rigid adherence to the sequence, nor any lack of integration or iteration of the generic activities [112]. Another distinctive depiction of NPD can be found in the form of a circularly structured model of the Delft product innovation process by Buijs [121]. By not having the beginning nor the end, it suggests that introducing of new products results in reaction of competitors and new insights from the market, which are then reused as inputs for the following NPD projects. Moreover, such representation aligns with the argument that there is no clear beginning, middle and end to the NPD process, since, for example, one idea can prompt several products being developed [111].

A comparison of stages and activities described and prescribed within the aforementioned NPD literature is shown in Table 2.1. Throughout the years, the number of stages and nomenclature have been changing, but the basic prescription of the process persisted. The emphasis on decomposing the early stages as opposed to technical development and manufacturing is not surprising, considering that the focus of NPD literature is primarily on integrating the concept design activities with other front-end activities (e.g. market, customer and business analyses, and comprehensive screening before the product design is finalised).

Simpler decompositions usually resulted in only two to three stages [122]. For example, Im et al. divide the process solely into the initiation and the implementation stage [123]. Lagrosen differentiate the idea, the development and the launch stages [124]. In a similar manner, Durmusoglu and Barczak separate the discovery, development and commercialisation [125], while Frishammar and Ylinepaa use the notions of early, mid and late stages [126]. In these representations, the conceptual design development activities are related to the first stage (front-end), while detail design is conducted within the second stages, prior to commercialisation.

Although the comprehensive approaches to NPD provide primarily a macro-perspective of the design process, some interesting insights for team activity and interaction can be found. For example, the early stages require more interdisciplinarity, either by temporarily integrating experts within the project team or via communication outside the team boundaries.

Table 2.1 Comparison of NPD stages and activities as prescribed in selected literature

STAGE	ACTIVITY	Cooper [5], [109], [110]	BAH [113], [114]	Page [6]	Griffin [7]	Song and Montoya-Weiss [115]	Crawford and Di Benedetto [12]	Pugh [118]	Andreasen and Hein [119]	Ulrich and Eppinger [120]	Fairlie-Clarke and Muller [112]	Bujis [121]
Strategy development	Product line planning				●					●		○
	Product strategy development		●		●	●	●			●	●	●
Product screening	Product idea generation	○	●	○	○	●	●		○	●	●	●
	Market screening		●			●	○		○	●	●	
	Technical screening	●				●	○		○	●	●	
	Product idea evaluation		●	○	○	○	●			●	●	●
Business and market analysis	Market research	●	●			●	●	●	●	●	●	●
	Business analysis	●	●	●	●	●	●	●	●	●	●	
Technical development	Concept development	●	○	●	●	●	●	●	●	●	●	○
	Concept evaluation		○	●	●	○	●	●	○	●	●	○
	Detail design and engineering	●	●	●	●	●	●	●	●	●	●	●
Testing	Technical design testing	●	●			●		●		●	●	○
	Commercial design testing	●	●	●	●	●	●	●		○	●	○
	Trial production	●					●		●	●		○
Commercialisation	Production	●		●	●		●	●	●	●	○	●
	Market launch	●	●	●	●	●	●	●	●	●	●	●

● Activity discussed as part of NPD process
○ Activity acknowledged, but not explicitly included in process decomposition

These insights confirm the importance of conceptual design stage for the integration of the technical and market aspects of product development. Nevertheless, functionally distant tasks (such as the engineering design activities), are often separated in the concurrent flow of activities [111], [112]; hence interdisciplinarity is not present at all times. The studies also reveal that as projects advance, stages are related to different types of activities, such as group ideation and decision-making in early stages and the individual, technical, engineering work in the development stage.

2.1.2. NPD stage-level information processing

The best practice studies have shown that successful NPD projects include ideation, screening and assessment activities in the front-end stage (see Table 2.1). Hence, in the early stages, teams conduct idea generation [42], [114] and then select the most promising opportunity idea [5]. Preferably, this decision is made based on the information gathered through the market and technical screening activities [115]. Further steps combine investigation of the market and financial analyses to build a business case. Here, again, information about the user and market needs is collected, and economic analyses are performed, prior to another step of feasibility assessment. At this point, the technical aspects of the product can enter the development stage, where the concept design is being detailed into an actual physical assembly or service. Once developed, the product can undergo testing – another particularly emphasised step in the NPD literature [6], [7], [9], [109], [110]. During testing, the product is being validated in-house and on field, and if necessary, trial sells and production activities are performed. The last stage is the production and commercialisation stage, where the designed product is being manufactured and launched onto the market.

As argued in the introduction, the activities in the design process represent information processing acts performed by members of the design team [76], [77]. Similarly, the overall NPD process and the stakeholders involved can be described as an information processing system. Given the information-processing perspective, the NPD represents an interlinked sequence of information processing activities which translate the knowledge of market needs and technological opportunities into information assets for production [127]. Namely, by processing the development information, NPD stakeholders formulate product specifications, concepts, and design details, as long as all the information required to support production and sales has not been created and communicated [120]. According to the stage-gate representations of the NPD process, the stages reflect the state of the developed product (in terms of information collected, generated, clarified, etc.), while the gates represent decision points, at which the project is assessed based on the available information.

Studies suggest that acquiring, interpreting and sharing new information improves NPD decision-making [128]. Hence, there exist information requirements which define the purpose of stages in the process, whereas each stage is designed to gather particular information in order to reduce the uncertainties before decision-making [110], [122]. Consequently, the research efforts which utilise the information processing view of NPD have mostly been focused on determining the information inputs and outputs for particular stages and decision points. For example, the ideal inputs of design-focused activities should include explicit assessments of user needs and technical requirements for concept development, and customer and production information for detail design [111]. The first should result in information about key attributes that need to be incorporated into the product and major technical cost, and the latter should finalise product specification [111].

In general, information processing within the stages of NPD related to the development of technical systems [129] involves recording, retrieving and reviewing of information [130], gathering, sharing and using of market information [131], acquisition, dissemination and implementation of information [132], [133]. In terms of design information, the NPD process has been considered an evolutionary process with design information being generated, transformed, and converged into the final product solution [134]. It can be argued that design teams implement the gathered (acquired and disseminated) market information, such as user needs and requirements to generate and transform a range of design information alternatives, before converging to a set of design information representing the final product design. However, studies with an overall perspective on the NPD process provide no clear insights on what the dominant mode or interaction of different modes of design information processing during the particular NPD activities is. These insights must be explored within the plentiful of theoretical and methodological research which describes and prescribes information processing during the specific types of development activities (some of which is presented later in this chapter).

2.1.3. Categories of NPD projects

The proficiency and engagement in conducting general steps of the NPD process (as shown in Table 2.1), is very likely to be affected by the type of the product being developed [115], and the uncertainty and risks inherited by the particular product category [12]. While several dimensions could be used for NPD project categorisation, the most useful relies on describing the degree of change a project presents to the development team. Hence, the types of NPD projects are typically categorised in terms of the type of innovation they exhibit. Innovation, here referred to the creation of a product, service or process, can fall on a continuum ranging from “continuous” (evolutionary progress) to “discontinuous” (revolutionary progress) [135]. Researches have used different notions to categorise projects across this continuum. Garcia and Calantone provide an extensive overview of constructs and scales of technological innovation in the NPD literature [4] and show that the division of the continuum ranges from two up to eight levels of innovativeness. The most common, however, are the dichotomous and the triadic categorisation. On the discontinuous end of the dichotomous categorisation are the radical, really new, breakthrough, original and true innovations, while the continuous end includes the opposite notions of incremental, routine, reformulated and adoption. The triadic categorisations add constructs such as more innovative, platform, new generation and moderately innovative in the middle of the continuous-discontinuous spectrum.

A comparison of typical categories of NPD projects is shown in Table 2.2. Holahan et al. define radical, more innovative and incremental product innovation by utilising the standard project typology scheme [12], [136], which originates from the studies by BAH [113]. They define **radical** product innovations as products that are new to the world and do not yet exist on the market (both technological and market uncertainty) [137]. The **more innovative** projects include product lines that are new to the firm (but not to the market), additions to existing product lines, and next-generation advances of products currently produced by the firm (either technological and market uncertainty) [137]. Finally, the **incremental** product innovations include improvements and revisions of existing products, repositionings (products that are retargeted for new users or applications) and cost reductions as the least innovative (netiher technological nor market uncertainty) [12].

Table 2.2 Comparison of typical new product categories based on their innovativeness

<table>
<tr><th>Holahan et al. [137]</th><th>Clark and Wheelwright [138]</th><th>Booz Allen Hamilton [113]</th><th>Ulrich and Eppinger [120]</th></tr>
<tr><td rowspan="3">Radical product innovations</td><td rowspan="3">Break-through development</td><td rowspan="3">New-to-the-world products</td><td>Technology-push products</td></tr>
<tr><td>High-risk products</td></tr>
<tr><td rowspan="2">Generic (market-pull) products</td></tr>
<tr><td rowspan="3">More innovative product innovations</td><td rowspan="3">Platform or generational</td><td>New-to-the-firm products or new product lines</td></tr>
<tr><td rowspan="2">Additions to existing product lines</td><td>Platform products</td></tr>
<tr><td rowspan="2">Complex systems</td></tr>
<tr><td rowspan="4">Incremental product innovations</td><td rowspan="4">Derivative or incremental</td><td rowspan="2">Improvements and revisions to existing products</td></tr>
<tr><td rowspan="3">Customized products</td></tr>
<tr><td>Repositionings</td></tr>
<tr><td>Cost reductions</td></tr>
</table>

The notions of break-through, platform or generational, and derivate development introduced by Clark and Wheelwright [138] can be directly mapped onto the radical, more innovative and incremental categories respectively. However, they add a category of **research and**

development (R&D) and advanced development to characterise projects focused on the creation of knowledge (technological explorations and investigations) as a precursor to commercial development [138]. Since these types of projects do not directly result in the development of technical systems, they have not been included in the comparison.

The associated risks and uncertainties of new product categories shown in Table 2.2 can best be described using the common variants of the product development process proposed by Ulrich and Eppinger [120]. These common variants can also, to some extent, be mapped onto the discontinuous-continuous innovation spectrum. For example, product development projects of highest uncertainty and risk (technical or market) concern the development of **technology-push** and **high-risk products**. The first utilises the "know-how" gathered through technological explorations and investigation to introduce new proprietary technologies to the market, and the latter entails unusually large uncertainties related to the technology or market, however, in the end, both are likely to introduce new-to-the-world products [120]. **Generic products** reflect the general stage-gate process, where product development starts with a market opportunity and then uses whatever available technologies are required to satisfy the market need [120]. Such a process can result in both new-to-the-world and new-to-the-firm products. Additions to existing product lines are usually based on **platforms**, where products are built around a pre-existing technological subsystem. At larger scales, platform products can be developed as **complex systems**, which comprise of many interacting subsystems and components. Different parts of complex systems can exhibit different levels of innovativeness; however, these are usually incremental improvements. Finally, **customised products** are the least innovative, as they represent slight variations of standard configurations and are typically developed in response to specific customer orders [120]. Ulrich and Eppinger introduce three additional variants of the generic product development process (process-intensive products, quick-build products and product-service systems) [120]; however, these processes do not involve the development of technical systems. In Andreasen and Hein's IPD textbook, the characteristic types of new product development are more abstract and include **updating/replacing** existing products on existing markets as the incremental product innovation, **adaptation** of existing products for new areas of application or **supplementing** current areas of application with new products as more innovative product innovations, and diversification as the highest degree of innovation, in which new products are developed for new applications [119]. Aware that contemporary organisations often combine in-house and outside development, Andreasen and Hein provide different outsourcing strategies for organisations such as manufacturing firms, design companies, sales agencies, and other [119]. Various strategies are reflected in different starting points within the NPD process skeleton (e.g. across Table 2.1); however, the sequences of the core development activities persist.

As emphasised by Garcia and Calantone [4], the reciprocal mapping of project typologies used across the literature is by no means straightforward, and the categories do not necessarily coincide as shown in Table 2.2. However, the separation of two extremes on the innovativeness continuum has provoked studies on the appropriate NPD practices for incremental, more innovative and radical product innovations. The studies generally agree that the development of really new products demands different approaches when compared to incremental product innovations. One of the first large scale studies (163 really new and 169 incremental products) was conducted by Song and Montoya-Weiss [115], who observed the perception of technical development as a most important stage for both types of innovation. Moreover, business and market opportunity analyses were perceived as more critical for radical innovation and strategic planning for incremental innovation. Such practice has been found counterproductive, as customer needs of really new products are often ill-defined and competitor capabilities are not clearly established. Thus detailed market studies provide no great value [115], particularly in the form of inputs for the subsequent technical development activities. Song and Montoya-Weiss explain that it is likely that customer requirements and technological capabilities co-evolve throughout NPD [115], which is aligned with the findings from the design literature presented later in the thesis. Their research prompted a number of new studies aimed at investigating the practices specific for incremental, more innovative and radical product innovations. The most relevant findings have been summarised in Table 2.3.

The succeeding studies have thus shown that radical projects are usually managed less flexible than incremental (e.g. in terms of skipping or overlapping gates) and include formal idea generation practices more often [137]. Also, radical product innovations are likely to exhibit more iteration [120] and require more information processing [139], [140]. Incremental projects often have abbreviated early front-end stages (or none at all), whereas radical projects have messy, chaotic and fuzzy front-ends before the formal NPD process [141]. Moreover, the front-end activities of radical and incremental innovations differ extensively in the way in which problems are structured and in which information searches are initiated [142]. Differences have also been found in the project review practices. Incremental projects exhibit more efficient project reviews, which is reflected in a smaller number of review points and higher proficiency in using evaluation criteria when deciding on project continuation/termination [8]. Finally, the

NPD process itself is more exploratory and less customer-driven for radical product innovations and includes often implies earlier development of prototypes [135].

Table 2.3 Selected findings regarding differences between incremental and radical projects

STUDY	INCREMENTAL PROJECTS	RADICAL PROJECTS
Relative rankings of critical development activities [115]	1. Technical development 2. Strategic planning 3. Commercialisation 4. Idea development and screening 5. Business and market opportunity analysis 6. Product testing	1. Technical development 2. Business and market opportunity analysis 3. Commercialisation 4. Idea development and screening 5. Strategic planning 6. Product testing
Process flexibility [137]	More flexible: – skipping gates: 60% – overlapping gates: 46%	Less flexible: – skipping gates: 38% – overlapping gates: 36%
Idea generation practices [137]	Informal / entrepreneurial	Formal
Iteration [120]	Less	More
Information processing (via communication) [139], [140]	Less (routine incremental)	More (nonroutine radical)
Early front-end activities [141]	Abbreviated or none at all	Messy, chaotic, fuzzy
Problem structure initiation [142]	– Identified and/or structured by organisation – Directed to individuals for information search	– Identified and/or structured by individuals – Individuals direct and conduct information search
Project review practices [8]	– Less review points – Higher proficiency of evaluation criteria usage	– More review points – Lower proficiency of evaluation criteria usage
Nature of development [135]	– Less exploratory – More customer-driven – Later prototyping	– More exploratory – Less customer-driven – Earlier prototyping

From the design perspective, the insights on exploration and constraints tend to be similar. Andreasen and Hein claim that it is not the sequences of activities that create the difference between very innovative and less innovative projects, but the extent to which things are predetermined – the so-called “degree of freedom” a design has [119].

Insights summarised in Table 2.3 will be used to define the parameters of the computational experimental studies of adaptive and innovative design projects (Chapter 6). To better explore the design and development stages of technical systems development, the following sections shift focus to textbook knowledge and research in engineering design (and design in general). This body of literature provides higher granularity depictions of the technical development stages, as well as dominant modes of information processing appearing throughout the process.

2.2. Engineering design process

In the engineering design literature, technical development is often portrayed as a series of stages, each of which further concretises the design by creating more information about it [49]. Textbook knowledge in the engineering design domain is based primarily on the industrial practice observed by the early researchers. Unlike the NPD literature which encourages an approach of incorporating a comprehensive set of product development activities (especially marketing activities), engineering design research gives more attention to the designing as the core of technical development. Engineering design textbooks supply engineers with systematic approaches, methods and tools for dealing with common engineering design problems. Due to their establishment in engineering design education, the prescribed methods and procedures are likely to be followed in real-world development organisations. At the same time, descriptive research and empirical studies provide feedback on how design is really performed.

2.2.1. Stages of engineering design process

Several relevant textbooks on engineering design (and product development in general) have been reviewed in order to discern the main stages in the development of technical systems. Here presented review aggregates the common design steps prescribed in these textbooks. The in-detail review included the following:

- Pahl and Beitz: *'Engineering Design – A Systematic Approach'* [41]. One of the most widely referenced models of engineering design, both in industry and education (several textbook editions) and a foundation of VDI 2221 guideline [144] for systematic development and design of technical systems and products.
- Hubka and Eder: *'Engineering Design'* [101]. A comprehensive procedural model of technical systems development. The model builds on the concept of a transformation system, which has been introduced throughout Hubka and Eder's previous work [105], [143]. In short, each transformation consists of a transformation system which transforms operands from one state into another by utilising effects given by the operators (e.g. humans, tools, environment, etc.). In the case of technical systems development, the design process is transforming needs, requirements and constraints of a technical system into a detailed description of a technical system (e.g. instructions for what would need to be manufactured) using the effects of engineering designers and their working means,

methods, management and environment. The same approach was utilised in *'Introduction to Design Engineering'* by Eder and Hosnedl [144].

- Ullman: *'The Mechanical Design Process'* [145]. Another well-accepted textbook gives an overview of the product development process with a particular focus on mechanical design and the accompanying tools and methods. Ullman expands the traditional engineering design process with product discovery and planning stages and associates them with organisational rather than with project activities.
- Cross: *'Engineering Design Methods: Strategies for Product Design'* [146]. Based on the review of prescriptive and descriptive design literature, Cross introduces a model of designing that integrates the procedural aspects of design with the structural aspects of design problems. Cross emphasises that the stages and accompanying design methods should not be assumed to constitute an invariant design process.
- Eggert: *'Engineering Design'* [147]. The textbook makes a distinction between engineering analysis and engineering design. A solution to an analysis problem is a predicted behaviour, and that the solution to a design problem is a form. Performing engineering analysis means formulating an analysis problem, solving it and checking the results. Performing engineering design on the other side means formulating a design problem, and then iterating between generating and analysing alternatives, and, in the end, evaluate the feasible ones. Eggert notices that engineering analysis is a part of the engineering design process.
- The review also included *'Product design and development'* by Ulrich and Eppinger [120] and *'Integrated Product Development'* by Andreasen and Hein [119], which have been preliminarily discussed within the previous section. Both books represent the processes and methods from three main perspectives: marketing, design and production, thus proving the need for integrating these disciplines during development projects.
- Several additional textbooks have initially been screened, including *'The Engineering Design Process'* by Ertas and Jones [148], *'Engineering Design'* by Dieter and Schmidt [149], *'Engineering Design Process'* by Haik and Shahin, and *'Engineering Design: A Project Based Introduction'* by Dym et al. [150]. However, the provided decompositions of the engineering design processes to a large extent coincide with what is reported within the aforementioned literature; hence a more extensive review of these books was omitted.

There exist many commonalities across the textbooks, particularly in high-level process descriptions. Firstly, the definitions of stages are similar, particularly regarding task clarification, conceptual design, embodiment, and detail design stage. Some authors include project planning activities as part of the design process (e.g. [41], [119], [120], [144], [145]), while others assume product idea as an already developed input to the design process. On the other hand, some of the models expand the late-design, by separating stages such as production ramp-up [119], [120], product support [145], and organisation and documentation of design outputs [150]. A common process of technical systems development can be outlined based on the aggregated steps. Such a process consists of five stages which are further decomposed into core engineering design tasks, as shown in Table 2.4. The stages have been described as follows:

1) **Planning** is usually performed before the approval of the product development project. For this reason, only several textbooks consider planning task as part of the engineering design process. Planning stage typically starts with the analysis of the situation in the market and organisational context. Once the organisation develops an understanding of competitors' products and own competence, it can start searching and evaluating product opportunities (product ideas). Various sources of opportunities exist, both within and outside the organisation. Product ideas which have been evaluated as feasible and align with the organisation's strategy become product development projects. A product definition together with resource allocation and schedules are formulated as project inputs.
2) **Task clarification** is performed to determine clear project aims and collect and define requirements and constraints to be fulfilled by the technical system. Designers first gain an understanding of the problem and any new information to the product definition. Depending on the type of a project, the stage can also include a detailed investigation of the state-of-the-art concerning similar products on the market and identification of customers' needs. Designer's involvement in identifying customer needs is encouraged, and a number of methods for these tasks are provided in the textbook. Once a sufficient amount of information has been collected, design teams develop product specification – an accurate description of what the product has to do in the form of requirement, constraints. It is not unusual for product specification and requirement list to be adapted on several occasions throughout the development process.
3) **Conceptual design** is on average given the most attention in the textbooks and is described as a stage that transforms requirements into concepts – functional models of the product being developed. It generally starts by abstracting the design problem and establishing a function structure as a refinement of the functional requirements. By

decomposing the main product function into sub-functions, the team can focus on what the product must do, rather than how it will do it. Designers then address each sub-function and transform them into a larger number of distinctive working principles which, to a varying extent, fulfil the sub-functions. The combination of working principles on the level of the function structure forms the basis for concept alternatives. Such a systematic approach is suggested to facilitate the generation of diverse concepts. In order to select the most suitable concept solution, teams evaluate concept alternative and make a decision which alternatives (one or multiple) will be developed in detail. The team can refine the selected concept alternative before a final concept proposal is documented.

4) **Embodiment design** can encompass several highly iterative design steps, depending on the type of technical system being developed. First, the product architecture is resolved by defining the overall layout of the technical system, primarily by arranging the components and defining modules for more complex designs. Configuration design involves the definition of components' forms, materials, manufacturing processes and the corresponding analyses (e.g. calculation and simulation). Designers often utilise Design for X (DfX) principles to address the issues of manufacturability, assembly, reliability, ergonomics, costs, maintenance, environment, safety, etc. The resulting preliminary design again needs to be evaluated. Once the main decisions about the main form, materials and manufacturing have been made, the design can be optimised (e.g. parametric analysis) and tested (prototyping). It is important to notice that prototyping might appear at several points earlier in the process. However, most textbook highlight it's importance within the embodiment design stage. Moreover, as the team approaches the final design and the associated production processes, a detailed more cost analysis can be performed. Preliminary part lists and production documentation are prepared as stage outputs.

5) **Detail design** concerns the finalisation of documentation related to the design of the technical system, such as the final product specification, detail drawings of parts and assemblies (with tolerances and surface properties) and bill of materials. The final documentation also includes instructions regarding production, assembly, transport and operation. Although many formal meetings have been made up to this point in the process, a final design review is desirable towards the end of an engineering design project. The final design review is the most structured and comprehensive one and results in a management's decision on whether the product design is ready for production.

Table 2.4 Overview of core engineering design tasks prescribed in the reviewed textbooks

STAGE	TASK	Pahl and Beitz [41]	Hubka and Eder [101]	Ullman [145]	Cross [146]	Eggert [147]	Ullrich and Eppinger [120]	Haik and Shahin [151]	Dieter and Schmidt [149]	Dym, Little and Orwin [150]
Planning	Situation analysis	●					○		○	
	Opportunity identification	★		●			★		○	
	Opportunity evaluation	★	○	●			●		○	
	Economic analysis		○			○	●		●	
	Product definition	●		●		●	●		○	○
	Resource allocation and scheduling	●	○	●		●	●			
Task clarification	Problem clarification	●	●			○				●
	State-of-the-art (competition) research		●	●		●		●	●	
	Customer needs identification	○		●	○	●	●	●	●	○
	Product specification	★	●	●	★	★	●	★	★	★
Conceptual design	Function structure development	●	●	●	●	●	●	●	●	●
	Working principles search	★	●	★	★	★	★	★	●	★
	Concept generation	●	●	●	●	★	★	○	★	★
	Concept evaluation	★	●	●	★	★	●	●	★	★
	Concept selection and refinement	★	●	★			★		★	○
	Document concept decision			●		●				
Embodiment design	Architecture design	●	●	●		●	●		●	
	Configuration design (form, materials, calc.)	●	●	●		●	○	●	●	●
	Design for X	●	○	●		●	●	●	●	●
	Preliminary design evaluation	★	●	○		●			○	○
	Optimisation	●	●	○		●	○	●	●	●
	Prototyping and testing	○	○	○		●	●	●	●	●
	Cost analysis	●	○	●				●	●	○
	Preliminary documentation preparation	●	●					●		○
Detail design	Detail drawings elaboration	●	●	●		●	●		●	●
	Procedures and instructions documentation	●	●	●		○				●
	Final design review	○	○			○			●	

● Task discussed as part of the engineering design process
○ Task is optional, not described in detail or included in different stage of engineering design process
★ Team activity is encouraged in solving the task

The comparison of design tasks included within the reviewed systematic approaches to engineering design (Table 2.4) reveals that the procedural models coincide predominately within the conceptual design stage. Moreover, some of the textbooks aim primarily on providing a methodology for the development of conceptual solutions (see, e.g. [50], [146]).

Hence, both design researchers and educators are aware that conceptual design makes the highest demands on designers and offers the most scope for improvements if the creative potential is properly harnessed [93]. In the embodiment, it is quite common for a need to arise for further conceptual design in respect of particular functions, usually minor ones.

The decomposition represented in Table 2.4 furthermore reveals that, for several design tasks, the textbooks encourage performing of team activities rather than individual work. Team activity is particularly favoured when the tasks require idea generation, or solution finding, evaluation and refining [41], [120], [145], [149], [150]. These insights facilitated the identification of team activities which have been experimentally investigated in Chapter 4, as well as structuring the conceptual design process simulated in computational experiments in Chapter 6.

According to the majority of textbooks, team activities are most desirable during tasks such as defining product specification, searching for working principles, concept generation and evaluation, selection and refinement of concept solutions, and design reviews. Such recommendations suggest that one should search primarily within the conceptual design stage when investigating team design activity. Indeed, design research has shown that design teams tend to organise team sessions mainly during tasks related to concept proposal [61], [96]. Finally, it is important to notice that although most of the design work is performed individually, engineering design textbooks emphasise that well-communicated information and good teamwork are essential at all times. The following subsection explores the decomposed engineering design process in terms of prescribed information processing practices.

2.2.2. Information processing in engineering design

According to Lawson and Dorst [53], the systematic approach to design corresponds to the "design as problem-solving" paradigm. If designers are studied, whether individuals or teams [145], one can observe that they perform something similar to posing a problem, searching for solution alternatives, exploring and evaluating the consequences, and selecting the most suitable alternative – the so-called generate-evaluate-select pattern [53]. While this paradigm does not capture aspects such as creativity or learning, it can describe how designers process information.

Models of engineering design acknowledge the problem-solving approach to designing. For example, Hubka and Eder define basic design operations – stating the problem, searching for solutions, evaluation and deciding, providing and preparing information, verifying, and representing – which are most frequently used by design engineers and are present during all activities [101]. Pahl and Beitz describe each stage as a journey through a problem-solving cycle, from problem confrontation and information collecting, followed by definition of objectives and main constraints, towards creation and evaluation of solution information. In the end, based on all information available, a decision is made about the final solution [41]. Similar descriptions of the problem-solving cycles are present in most of the reviewed sources, with some optional steps, such as the communication of decision instructed by Ullman [145].

Problem-solving requires a large and constant flow of information. Pahl and Beitz recognise three main categories of information conversion to describe problem-solving from the information processing perspective: reception, processing and transmission of information [41]. Information is received from different types of sources (formal and informal information gathering) and can again be transmitted by documenting (sketching, drawing, reporting, etc.) or verbally communicating information. On the other hand, information is processed by performing analysis and synthesis, concept development, calculation, experimentation, layout elaboration, solution evaluation [41]. Maarten Bonnema and Van Houten utilise Krumhauer's [152] perspective and argue that information processing modifies the conceptual design space in three dimensions: complexity, concreteness and realisation. "Abstraction" information process decreases concreteness and "search for solution" increases both concreteness and realisation of design, while "division into subproblems" decreases and "combination and selection" increases complexity [32]. Such a description of design problem-solving aligns with the arguments made in the introduction: when solving design-related problems, human designers can be regarded as information processing systems (IPS) [153].

The IPS perspective is not present in prescriptive design research only. A lot of what is known about design cognition and human designers' problem-solving stems from empirical research that utilises the IPS conceptualisation [154]. The resulting design theories aim at describing practices that are regularly taken as design, while prescriptive design theories aim to single out particular types of design practices and posit desirable properties about these practices [155]. For this reason, the problem-solving sequence of understanding, generating, evaluating and decision-making [145] can be discerned on different levels of the engineering design process [119]. On the project level, an overall, ill-defined complex problem is solved. On the stage level, the problem-solving steps can be recognised in the sequences of tasks (e.g. tasks within the conceptual design stage as shown in Table 2.4). Finally, at the lowest level, teams tackle simpler, more defined problems, preferably using different types of design methods.

In general, researchers agree that the design process is not linear whereby design problems could initially be fully defined and then solutions directly derived from them [66]. Empirical research has shown that in the case of ill-defined problems, designers do not typically start by pursuing to define the design problem rigorously [156]. They instead progressively and iteratively discover, structure and address the issues as they emerge in the design process [157]. The nonlinearity of the design process and the ill-defined nature of design problems is particularly evident during the conceptual design stage, which assumes reciprocating decomposition of design problems and exploration of possible solutions before a final concept is proposed [158]. A comparison of descriptive and prescriptive insights into the main information processes associated with conceptual designing is shown in Table 2.5. Even when designers follow a systematic problem-solving strategy (e.g. [159]), they continuously generate new task goals and redefine task constraints [160]. Two distinctive dimensions of design space – the problem space and the solution space – are developed through a constant iteration of ASE processes [161], [162]. These three fundamental information processes can be traced back to Asimow [163], who proposed ASE model as a general problem-solving strategy, and Watts [164], who presented the design process as iterative cycling through ASE. The evolution of problem- and solution-related information entities, which the result of ASE information processes is often regarded as “problem-solution co-evolution”.

Table 2.5 Comparison of information processes associated to the conceptual design stage

<table>
<tr><th>TASK</th><th>Pahl and Beitz [41]
Hubka and Eder [101]</th><th>Fiorineschi et al. [159]</th><th>Maarten Bonnema and Van Houten [32]</th><th>Cross and Dorst [161]
Woodehouse and Ion [75]</th></tr>
<tr><td rowspan="2">Function structure development</td><td rowspan="2">Problem defining</td><td rowspan="2">Analysis</td><td>Abstraction</td><td rowspan="6">Cycles of analysis, synthesis and evaluation</td></tr>
<tr><td>Division into subproblems</td></tr>
<tr><td>Working principles search</td><td rowspan="2">Solution creation</td><td>Information gathering</td><td>Search for solutions</td></tr>
<tr><td>Concept generation</td><td>Synthesis</td><td>Combining</td></tr>
<tr><td>Concept evaluation</td><td>Solution evaluation</td><td rowspan="2">Evaluation</td><td rowspan="2">Selection</td></tr>
<tr><td>Concept selection and refinement</td><td>Decision</td></tr>
<tr><td>Document concept decision</td><td>Communicating</td><td></td><td></td><td></td></tr>
</table>

The notion of problem-solution co-evolution has been introduced within the co-evolutionary model of designing by Maher et al. [165] and has been present in many studies ever since, especially within the creative design research. In the model, designers are iteratively developing concepts and exploring the two spaces, with each space informing the other. Maher and Tang later investigated co-evolutionary design as a cognitive and a computational model of design and demonstrated the similarity of reasoning between the human designer's cognition and computational algorithms co-evolutionary cycles [83]. However, studies have also shown that despite the commonalities in information processing employed by human designers, their focus on problem or solution space can differ and that the co-evolution strategies can be distinguished as a problem- and solution-driven [166].

Although the exists an overlap in how systematic approaches to engineering design prescribe the conceptual design stage (see Table 2.4 and [167]), Table 2.5 and the empirical research on the high-level information processing reveal that the conceptual design process is not straightforward and there is no linear or sequential representation of the information flows that could capture conceptual design information processing. Later sections will show that as the granularity of design process descriptions increases, the more flexibility and iteration is required in the models to capture the information processing.

2.2.3. Types of engineering design projects

Typology of engineering design is commonly associated with outputs of engineering design projects, that is, how distant the design outputs are from the current paradigm, primarily in terms of novelty [42]. The most referenced, simple categorisation was proposed by Pahl and Beitz [41], who proposed three types of design:

- **Original design** incorporates new solution principles which can be realised either by selecting and combining known principles and technology or by inventing completely new technology. The design of the original technical system is novel, without existing or predecessor systems [144]. Sometimes (but rarely) it is the identified need that is original [149]. The term is also used when existing or slightly changed tasks are solved using new solution principles [41].
- **Adaptive design** implies keeping known and established solution principles to satisfy a different need. The design team adapts the known solution (embodiment) to the changed requirements [149]. It may, however, be necessary to undertake original designs on the level of individual components or assemblies [41].

– **Variant design** involves varying the size or arrangements of components and assemblies within the limits of previously designed products [41]. The systems' function and solution principles remain the same, whereas some of the design parameters are changed [149]. As such, variant design implies a direct adoption of a previous technical system [144].

Howard et al. have compiled plentiful of analogous categorisations which can be found in design research [42]. Notions used to describe original design have thus included "new", "innovative", "novel", "radical" and "creative". Adaptive design has been described as "extensional", "strategic", "redesign" and "innovative", whereas variant design has been characterised as "transitional", "modular/architectural" and "configuration". One could suppose there exists a relation between these three categories of design with the previously discussed types of NPD projects, that is, original design with radical projects, adaptive design with more innovative projects and variant design with incremental projects (e.g. [168], [169]). While these two categorisations share many similarities, unification regarding originality and novelty is yet to be established [170]. For example, McMahon suggested that both adaptive and variant design can be classified as incremental [171].

Comparison of the three types of designs/design projects has been the subject of several studies. Selected findings are summarised in Table 2.6. Studies build upon the fact that for a variant design the function structure [41] and solution elements/patterns [172] of an existing product can be reused as a starting point for engineering development. Hence, the creative outputs, if any, are most likely to appear within the embodiment design stage [173], as a result of a structural level change in the technical system [42].

In adaptive design, the function structure is established by analysing the existing product and adapting the functions with respect to the new requirements [41]. The creative outputs are thus most likely to be functional [42] and appear during task clarification [173]. Therefore, as opposed to variant design, adaptive design can only partially reuse solution elements and patterns available within the adapted technical system [172]. On the other hand, the original design demands that the function structure is generated from scratch, based on the requirements list and abstraction of the given design problem [41]. The process can produce creative behavioural outputs [42], as a result of conceptual design efforts [173]. No or little a priori solution elements and patterns are available for original design [172]. It can thus be argued that the difference between the two ends of the novelty spectrum determines how far the formulation of the design problem needs to be abstracted away from the salient features of the design elements and patterns that perform similar tasks in similar technical systems [174]. This difference is reflected explicitly in the levels of uncertainty associated with the three types of design. For example, during the conceptual design stage, original projects exhibit the highest amount of uncertainty since no baseline product can be determined, whereas adaptive and variant designs present less uncertainty due to solution reuse. Nevertheless, as the development proceeds, the uncertainty continually decreases for all design types [44], [175].

Table 2.6 Selected findings on differences between variant, adaptive and original design

STUDY	DESIGN PROJECT TYPE		
	Variant	Adaptive	Original
Amount of conceptual design uncertainty [44], [175]	Small	Medium	Large
Function structure development [41]	Based on existing function structure	Based on analysis of existing products	Based on requirements list and abstract problem formulation
Use of existing solution elements and patterns [172]	Complete reuse of priori given solution elements/patterns	Partial reuse of priori given solution elements/patterns	No or little priori given solution elements/patterns
Creative outputs [42]	Structural level	Functional level	Behavioural level
Relative position of creative outputs [42], [173]	Embodiment design	Task clarification	Conceptual design
Dominant type of reasoning [176]	Deductive design processes	Inductive design processes	Abductive design processes

Additionally, the variant, adaptive and original designs can be associated with deductive reasoning (inferring an individual instance from a general principle or law), inductive reasoning (generalise a set of instances or observations) and abductive reasoning (creating a possible hypothesis that explains a set of observations) processes respectively [176]. Summers [177] explains that in the engineering design context, deductive reasoning takes place when the design variables and knowledge are given, and the design specifications are derived; inductive reasoning seeks to generate appropriate design knowledge based upon the given set of design variables and specifications; whereas abductive reasoning may be viewed as a mapping to possible design variables based upon the given design specifications. A similar view is provided by Lu and Liu [178], who represent deductive reasoning as a logic foundation of design analysis, inductive reasoning as a logic foundation of design evaluation and abductive reasoning as a logic foundation of design synthesis. Abductive reasoning creates new hypotheses, deduction analyses these hypotheses before induction justifies them [178]. Hence, within the variant design, the design team dominantly validates the appropriateness of an existing design and makes minimal adjustments on its design specification. In the adaptive design, the team analyses the current design and reuses some of the functions and solution principles, whereas, in the original design, the team must hypothesise the complete design.

There is no consensus on the proportions of original, adaptive and variant design in product development. In their study conducted in the UK industry, Culley et al. report 36% of original, 36% of adaptive and 28% of variant design projects [179]. According to Pahl and Beitz's study of mechanical design projects in Germany, 25% of them were original, 55% adaptive and 20% variant [179], [180]. Another UK-based study [181] revealed that original design was undertaken by 33% of the companies, adaptive by 92% and variant by 33%. All three studies are over 20 years old, and the data can be considered outdated. A more recent study [182] suggests that 83% of companies undertake adaptive, 57% original and 14% variant design.

In the context of here presented research, the focus is set on original and adaptive design only (see Chapter 6 for more details). Besides variant design being the least present in engineering design practice according to studies above, there are two interdependent reasons for such a constraint. First, since variant design assumes complete reuse of existing functional structure and solution principles and can only produce creative design in the embodiment design stage and at a structural level (see Table 2.6) the conceptual design stage can be partially or fully skipped. Second, it was mentioned that team activities are most likely to take part during the conceptual design stage (see Table 2.4). Hence, the insights that here presented research aims to provide can only be related to adaptive and original design projects, where a complete execution of the conceptual design stage is expected.

2.3. Team design activity

In the introductory chapter, it is highlighted that researchers adopt numerous perspectives of the engineering design process to study the activity of designing in teams. While there exist differences in the way researchers explore and model design, its multifaceted nature is well recognised [46], [53]. For instance, in their domain-independent descriptive model of design, Reymen et al. [183] introduce the notion of a design situation, which combines three facets of design: the state of the product being designed, the state of the design process, and the state of the design context. According to their model, designing is the activity of transforming the state of the product being designed or of the design process into another state towards the design goal. They also utilise the notion of design space to refer to possible states of information about the product and the process. The state of the design context, on the other side, is separated from designing and is changed by the stakeholders (e.g. user requirements, company norms, available production technologies, etc.). Moreover, while designing is affected by the context it takes place in, context-related information itself most often does not change within the time span of design activities [183], such as ideation or design review sessions. Hence, according to design situation viewpoint, team design activities represent sequences of designers' information-processing actions towards a design goal, which result in the evolution of information entities within the explored design space (transforming the state of the product and the process) considering the specific (static) design context.

Before the theoretical framework of team design activity can be comprehensively elaborated, several areas of relevant research on both individual designers and design teams are examined. As a starting point, the experimental studies of team designing are considered, as a means of decomposing the process into design operations and gaining a better understanding of what drives information processing in design teams. Next, the role of ASE design operations and design space information evolution across different models of the design process is investigated. Finally, insights into different types of team design activities are briefly discussed. It is important to notice that the examined areas are, however, not mutually exclusive. For example, the experimental studies often utilise observable design actions and the change in design space as a proxy for investigating the thinking processes of designers.

2.3.1. Experimental studies of team design activity

Given the viewpoint of design thinking as an underlying process of designing, particular attention in design research has been given to investigating, decomposing and modelling of designers' thinking processes. For many years now, design researchers have been employing approaches such as think-aloud and conversational methods, case studies and controlled experiments to explore the thinking patterns during the execution of design tasks [23]. Design thinking research is inspired by other disciplines currently studying collective thought, including social and cognitive psychology, organisational sciences and anthropology [184]. Fine-grain investigations of the designing have thus often been carried out using protocol analysis, currently the most suitable method of revealing the cognitive abilities of designers [161]. Reported protocol studies of design teams are mainly concurrent and conversational [185], meaning that the participants concurrently report on their thinking acts using conversation during task execution. The resulting cognitive models usually describe the iterative nature of designing in which design alternatives are repeatedly generated, analysed and evaluated through exploration and convergence [157], [186].

A noteworthy example is the "generic model of design team activity" by Stempfle and Badke-Schaub [54], who employed protocol analysis to capture regularities in thinking and reasoning processes underlying the problem-solving process of three laboratory teams. Their study proposes a process that matches the "natural" thinking process of design teams, where the generation of solution ideas is followed by immediate evaluation, except when there are any questions or misunderstandings. If such quick assessment yields a positive result, teams decide to accept the solution. Otherwise, new solution ideas are sought [54]. Ensici et al. [187] provided additional detail to the decision process by focusing on the phenomena of using and rejecting decisions, based on whether they have been included in the final solution. They decomposed the team design process into thinking processes related to decision making and identified the consequences of rejected decisions, such as narrowing the solution space and prioritisation, structuring and complexity reduction of the design problem [187].

In their analysis of collaborative sketching, Eris et al. [58] discuss the significant role of gestures in team designing. For example, they identify that gestures which construct conceptual relations between two sketches (cross-gestures) facilitate the shared understanding of designers. Sauder and Jin [56] focused on generative thinking processes of memory retrieval (when an experience or design entity that existed in the past is remembered), association (when connections are drawn between two design entities), and transformation (when a design entity is altered or changed). They observed that the stimulation occurring through questioning has the strongest relationship with the generative thinking processes. Cardoso et al. [188] investigated design thinking in teams during ideation as an inquiry-driven process. They observed patterns of cognitive moves triggered by reflection on dissatisfaction and facilitated by the formulation of high-level questions that steer the direction of the design discourse. Sung and Kelley [189] analysed sequences of cognitive strategies of design teams and identified a bi-directional iteration between designing and predicting, or simply put – introducing ideas and predicting possible consequences of the ideas.

Although the above-listed studies provide valuable insights into team design thinking, the used protocol coding schemes are closely tied to the specific context and the phenomena observed, making it difficult to directly compare the results and conclude how team design activity is affected by the change in design context or progress of the design process.

In contrast to the use of diverse coding schemes, there exists a portion of experimental design studies that investigate various aspects of design team thinking processes using a single coding scheme- the function-behaviour-structure (FBS) ontology of design and designing. These studies have accepted the axiom that *"the foundations of designing are independent of the designer, their situation and what is being designed"* [26]. Kan et al. [190] utilised the FBS ontology-based coding scheme to study an industry team brainstorming session and measure frequencies of transitions between FBS design issues and interactions on the individual and team level. Jiang et al. [55] applied the same ontological framework to study design cognition of small teams within the context of different disciplines and conceptual design tasks. They classified the teams' designing styles as a problem- and solution-focused. As an extension of that research, Gero and Jiang [191] studied the design review and critique sessions. Both studies reveal commonalities across designing but also identify the differences between design domains and design tasks. Gero et al. [192] investigated how different creativity techniques reflect in design cognition of team members during the concept generation activity. They coded the activity of eleven design teams and found a correlation between the structuredness of ideation techniques and design teams' focus on the problem or solution-related aspects of designing.

In the case of employing the unified FBS coding scheme, different episodes in the design process can be investigated and compared, particularly the cognitive processes regarding the design space (functions, behaviours and structures). However, FBS being an ontology that primarily describes the design as an artefact, the elements of the design process are derived from transitions between the coded segments, rather than being directly coded. Additionally, since only transitions between certain pairs of FBS design issues are assigned with micro-scale processes, the FBS coding scheme may not be suitable for direct coding of the design process.

Within the context of the presented research, the abovementioned experimental studies of team design thinking are relevant for two main reasons. Firstly, they provide valuable methodological insights into the development of a protocol analysis study (Chapter 4). Secondly, the studies have contributed an extensive collection of insights into different aspects of team information behaviour, which can be utilised for comparison, interpretation, validation and discussion of the research results (Chapter 7).

2.3.2. Design information processing in team design activity

All design processes are different unless examined at a very abstract level [193]. Studies aimed at unfolding the commonalities amongst designing in different domains confirm this by indicating that only at the high level of abstraction can information behaviour similarities between different domains be recognised (e.g. [183], [194]). Any comparison of different individuals, teams, activities, domains or methods, whether in search for similarities, patterns or differences, stems from the prerequisite of abstraction in modelling both the design process (e.g. design information processing) and the design space (e.g. design information entities). Therefore, the fine-grain descriptions of individual or small team design activities have predominantly been given in the form of abstract micro-scale models, which emphasise the iterative nature of designing and the need of responding to new information generated or revealed during the design process [49].

A well-adopted example of process abstraction implies design information operations of analysis, synthesis and evaluation (ASE), which have already been discussed as a means for meso-level modelling engineering design information processing. Information processes analogous to ASE can thus be identified across eminent descriptive models of design activity. For example, the “basic design cycle” by Roozenburg and Eekels [195] consists of analysis, synthesis, simulation, evaluation and decision. The “design steps” by Gero [196], which represent the transitions within the FBS ontology, include analysis, synthesis, evaluation, formulation and reformulations. These transitions are also present within the extensions of the FBS framework. For example, analysis, synthesis and choice can be used to describe routines such as identification of needs and formulation of requirements [197]. ASE has also been included in the “iterative processes” between the problem and the solution space in creative design by Dorst and Cross [161]. Their portrayal of ASE as fundamental design information processes in designing has been embraced across many studies in design research (see, e.g. [67], [198], [199], [200], [201], [202]).

The “generic step model” of design team activities by Stempfle and Badke-Schaub [54] consists of “generation”, “analysis”, “evaluation” and “decision”. The “integrated model of designing” (IMoD) by Srinivasan and Chakrabarti [203] classifies generic activities into “generate”, “evaluate” (which can also include analysis), “modify” and “select”. Abstraction using ASE can also be found within models of problem-solving in design [204] and creative process models [42], [205]. As mentioned previously, the ASE sequence was intended as a model of sequential stages in the design process but was often criticised for not reflecting the reality of design projects [160]. The more or less defined sequences of ASE were later incorporated within micro-scale models of design.

To avoid ambiguity, from this point on, the term **design operation** is adopted when referring to ASE as the observable fine-grain information processes that transform the state of design information entities (as opposed to the stages in the design process). Moreover, the design information entities manipulated by means of design operations will be referred to solely as **design entities**. Such conceptualisation is inspired by the study of Jin and Benami [36], who introduced the notion of design operations when referring to the observable, fine-grain acts of design information processing. In their generate-stimulate-produce (GSP) model, design operations are used to generate design information entities, which in return stimulate designer's thinking processes, leading to new design operations. The model gives a clear distinction between the observable aspects of the designing such as talking, writing and sketching, and the internal ones such as the underlying thinking processes of designers [36]. GSP was initially utilised to investigate creative patterns and stimulation of individual designers but was later expanded into collaborative thought stimulation (CTS), where design information entities are shared by team members [56]. However, since the CTS model regards design operations only as generators of design information entities (design information synthesis), the notion of design operation must be adjusted to reflect also the previously discussed analytic and evaluative design information processes (design information analysis and evaluation), which are performed in both the problem and the solution dimension of the design space.

The insufficiently understood role of ASE design operations in the co-evolution of the problem and solution space is in part a result of inconsistency in the interpretation of ASE as fine-grain steps in the design process. Firstly, depending on their purpose, the models of design tend to associate analysis to either the problem or the solution space. The prescriptive design models inherit the problem-solving interpretation of ASE, where analysis is information processing performed within the problem space and includes the understanding, decomposition and formulation of design requirements (e.g. [75], [159]). Although such instantiation of analysis can also be found in some of the descriptive approaches (e.g. [195], [206]), the others of the aforementioned descriptive models associate analysis to information processing within solution space, performed to increase the understanding of solutions prior to evaluation.

These models introduce concepts such as formulation [196], goal clarification [54] and problem definition [207] to summarise problem space information processing. Secondly, although synthesis has been shown to play an equally important role in developing both design problems and solutions [208], its integration as part of the ASE sequence within prescriptive and descriptive models is primarily in the form of generating solution-related information [209]. Thirdly, with new information entities populating the problem space as designing proceeds, the co-evolutionary process implies not only the need for evaluation of information about design solutions but also evaluation of the introduced requirements and constraints [83], [185].

However, the term evaluation has mainly been used to describe the assessment of design solutions concerning the problem being solved, e.g. in the FBS framework [55], problem-solving steps of design teams [54] or the creative processes in design [42], [205]. Problem evaluation remains a phenomenon that has not been explicitly included within the reviewed ASE design models.

The explored design space (problem- and solution) evolves as new design information entities are generated, and the existing ones are modified. Different types of design information entities appearing in the problem and the solution space have been abstracted in more-less similar ways. For example, the reasoning about requirements, functions and expected behaviour of the artefacts within the FBS ontology is related to the problem space, and reasoning about structure and behaviour as observed of the structure is related to the solution space [55]. Macmillan et al. [25] have used the terminology of needs, requirements and problems as conceptual design entities in problem space, and solutions, proposals and concepts as entities in solution space.

In their study of the solution- and problem-driven design, Kruger and Cross [166] categorised the problem entities into requirements and constraints. Sarkar and Chakrabarti [210] recognised requirements, related problems, constraints, solutions and evaluation criteria. Liikkanen and Perttula [158] used the terms goals and subgoals in the exploration of problem decomposition. On the other hand, the IMoD by Srinivasan and Chakrabarti [203] classifies entities of the problem-solution space solely into generic requirements and solutions, thus eliminating the issue of vague boundaries between some of the terms describing entities in the design space. For example, functions and behaviour (see, e.g. [162], [211]), needs, requirements and constraints [197], [212], or how ideas become concept solutions (e.g. [96], [213], [214]). Based on these findings, here presented research will not consider detail classification of design entities but will instead use the concepts of problem and solution space to cover the full range of design entity expressions (as shown in Chapter 3).

The generality and applicability of co-evolutionary design are yet to be comprehensively tested for team-based conceptual design. In their domain-independent descriptive model of design, Reymen et al. [183] have implemented the problem-solution co-evolution as a simultaneous evolution of desired and current properties. Hultén et al. [20] have related their model of ideation to problem-solution co-evolution by introducing the concepts of common ground and transformative closure. The first implies returning to the problem space with a new understanding of the problem, and the latter implies reaching a solution space that can develop and change during the process. They emphasise the need for conceptualising the common understanding (ground) as support for co-evolution within the models of designing in teams [20]. Recent studies support the co-evolution during collaborative activities such as ideation [46] and concept selection [215], but also throughout a series of real-world product design meetings [67]. Moreover, a study by Deken et al. [63] has shown an increased alternation between the spaces during conceptual design compared to the task clarification stage.

Finally, it must be noted that there also exists another stream of team design activity research focused on information processing associated with aligning the design process (planning of further steps, moderating, etc.). Nevertheless, a study aimed at understanding human information processing during team design tasks revealed that over two-thirds of strategies employed by the designers were searches through design space, as opposed to coordinating the design process [54], [77]. Moreover, focusing on the management of designing rather than the designing itself is more related to the research of team roles [57], coaching and leadership [37], experience and expertise [79], team adaptation [216], etc. For these reasons, here presented research concerns solely the information processing acts (design operations) related to creation and modification of design content information (design entities). The extension of these concepts within a theoretical framework is described in Chapter 3.

2.3.3. Common team design activities: Ideation and concept review

Ideation (idea generation) and concept review are considered core activities within the overall design process, due to their creative potential and impact on the final design outcomes [46], [215]. Significant research efforts have thus been directed towards prescribing approaches, methods and tools to facilitate the generation of high-quality ideas and selection of the best concept solutions in a particular context. The prescriptive research has primarily been aimed at boosting creativity and productivity, but also overcoming fixation and bias (please consult [217], [218], [219], [220], [221] for more details on recent findings concerning these issues). Although there are many formalised methods developed for ideation and concept selection, it is often suggested that designers prefer working informally rather than using the less intuitive and imposed methods [220], [222].

Understanding the designers' natural and intuitive approach to designing (both the cognitive and the observable process) is essential in providing teams with better support during activities such as ideation and concept review. Despite the acknowledged need for understanding the naturally occurring information processing in design, fine-grain decomposition of ideation and concept review processes has rarely been in focus of design research. Moreover, the comparison of the two activities is, again, hindered by the use of different coding schemes, team formations, design environments, etc. Nevertheless, some additional process and behaviour patterns identified across the protocol studies of ideation and concept review are discussed below.

Sarkar and Chakrabarti [210] studied idea generation of individual designers and identified different patterns of design space search taking place during problem understanding, solution generation, and solution evaluation, and related the types of searches to solution quality. They later propose a model of ideation where, given an unsolved problem, designers find an existing, related solution from the past (from memory), and then they modify it for the current problem, whether in the phase of problem formulation, solution generation or solution evaluation [223]. Liikkanen and Perttula [224] also perceive ideation as a memory-based activity which consists of memory sampling and idea production. They pointed out that individual designers generate similar initial ideas before contextual cueing and verbal stimulation are introduced. However, a semantically substantial and associatively rich change of context and verbal stimulation are shown to alter the ideation process.

Stimulation has also been studied on team-level. López-Mesa et al. [225] studied the effect of stimuli coupled with individuals' problem-solving styles on the ideation process of design teams. They argue that stimulus with images leads to a higher quantity of solutions, while stimulus by idea-prompting checklist favours refinement of solutions. Sauder and Jin [56] employed retrospective protocol analysis and found that collaborative prompting and clarification have a strong relationship with remembering design entities, while collaborative seeding and correcting strongly correlate to altering and changing design entities.

Cash and Štorga [46] have explored what drives innovation by using network analysis to link ideation to the engineering context and the broader design process. Insight derived from the networks include identification of decoupled ideation, characterised by producing numerous solution ideas, and integrated/iterative ideation, expressed in co-evolution of design problems and solutions. Hatcher et al. [226] have embodied Linkography to compare the creative processes when two different ideation methods are used (brainstorming and an approach proposed by the authors). Their findings include, for example, that brainstorming has a less structured approach and is more likely to contain a higher number of idea moves (idea generation) inspired by non-idea moves, such as questions (idea analysis).

Protocol studies of concept review (and the more general design review) activity have primarily been in focus of design research with educational implications (see, e.g. [227]), such as guidelines for mentors who provide feedback, advice or critique. However, little is known about the team-based concept review process and how teams select creative ideas [61]. Moreover, while concept review is generally described as a convergent activity [220], Toh and Miller [215] note that team members often not only evaluate and select concepts, but also combine, modify, and propose new solution ideas. They point out that teams who pursue to generate new ideas during concept review tend to select more creative concepts.

The FBS framework has also been used to investigate different types of design activities. As mentioned earlier, it was employed to study design cognition during both ideation (e.g. [55], [190], [192]) and concept review [191]. Since the FBS ontology offers commensurability of study results [26], these studies can be qualitatively compared. Gero and Jiang [191] identified the similarity between the two activities in the linearity of cumulative occurrences of structure and behaviour issues, however, they noticed that unlike designing (ideation), concept review activity does not exhibit the decrease in the ratio of the problem- and the solution-related discussion as the session progresses. Aside from these efforts, the micro-scale descriptions of how teams synthesise, analyse and evaluate design entities during concept review remain undeveloped.

Within the context of the presented research, the studies of ideation and concept/design review offer insight into key characteristics of these activities, thus complementing the general findings resulting from experimental research on team design thinking when discussing the protocol analysis results in Section 7.3.

2.4. Research gap

The overview of research on team design activity in the context of engineering design and product development has facilitated the identification and formulation of the primary research gaps. The gaps particularly concern the agreement on definitions of analysis, synthesis and evaluation as fundamental operations in design problem-solving and their application in exploration of the problem and the solution dimension of the design space; as well as lack of understanding on how the team problem-solving process is adapted as teams progress in conceptualisation of the technical system. The gaps are briefly discussed hereafter and summarised in the form of research questions which are addressed later throughout the thesis.

Given the perspective of the simultaneous evolution of design problems and solutions [161], and ASE being regarded as different modes of conceptual thinking [75], the context of presented research calls for adopting the definitions of ASE as design operations performed in both the problem and the solution space. Rather than attributing information processing either the problem or the solution space, the formulated definitions of ASE should highlight the differences between analysis, synthesis and evaluation as fundamental information processing mechanisms for evolving the design content.

RQ1 Can analysis, synthesis and evaluation be conceptualised as fundamental information processing mechanisms that design teams perform to manipulate both the problem- and solution-related design information content?

Moreover, as shown throughout the thesis, both the notion of problem-solution space and ASE as fundamental information processing mechanisms have regularly been employed in investigation and modelling of design activity. Nevertheless, while the proposal of problem-solution co-evolution in design research [165] has been around for over twenty years, the questions of how exactly ASE sequences iterate and intertwine throughout the conceptual design stage, and in what way these patterns differ for the problem and the solution space, have not been extensively explored. For example, the fine-grain approaches, used to understand the details of micro-scale cycles [49] in conceptual design activities, have either employed ASE sequences within the solution space (e.g. [54], [192]), neglected the evolution of both spaces (e.g. [159]), or focused solely on individual designers (e.g. [206], [210]). Insights into patterns of ASE and the evolution of the explored design space should complement the existing models of team design activity and increase the understanding of team conceptual design process.

RQ2 What patterns of ASE altering inside and in-between the problem and the solution dimensions of design space can be identified during team conceptual design activities?

Additionally, experimental studies have generally been tied to only a specific type of conceptual design activity, such as ideation (e.g. [188], [192]) or concept review and selection (e.g. [61], [215], [221]). The utilisation of diversified team compositions, coding schemes and modelling approaches in these studies hinders direct comparison of the results. Because of the inability of a proper inter-study comparison and due to the lack of studies offering a simultaneous investigation of team designing across different activities, such as ideation and concept review, there exists little insight on how the micro-scale design process patterns are affected by the design activity goal and team’s progress within the conceptual design stage.

RQ3 In what way do the identified patterns of ASE design operations differ for different types of team conceptual design activities, particularly for ideation and concept review?

RQ4 In what way are the identified patterns of ASE design operations likely to change with the progress of the conceptual design stage?

Finally, the reviewed literature shows that while teamwork is expected during the entire NPD process, the team design activities, where a group of designers explicitly work together on a design task, are encouraged mainly within the conceptual design stage. As such, team activities within the conceptual design stage have been given significant attention, and there exist efforts to model different aspects of team designing, including information processing and interactions in teams. Nevertheless, the overall context stemming from NPD and the engineering design process within it remains neglected. In particular, there exist no insights on how information processing and interactions in teams are affected by the novelty of the technical system being design, despite it being the primary way of categorising projects in both NPD and engineering design literature.

RQ5 What are the prevalent patterns of ASE design operations in different types of engineering design, particularly regarding the novelty of the developed technical system (innovative and adaptive design)?

The research questions are tackled in two steps: theoretical and experimental. The first, theoretical step focuses on synthesising the relevant literature findings and development of a model of information processing in team conceptual design activity, thus addressing the RQ1 (Chapter 3). In the experimental part, a protocol analysis study and computational experiments are conducted in order to provide the answers to research questions RQ2-RQ5 (Chapters 4 and 6).

3. THEORETICAL FRAMEWORK

In this chapter, the most relevant insights from the reviewed literature have been synthesised into a single theoretical framework. Three main parts can be discerned. First, the definitions of analysis, synthesis and evaluation as design operations within both the problem and the solution space are formulated. Second, the design operations and spaces are incorporated into a state-transition model of team conceptual design activity. Finally, the theoretical framework is encompassed by identification, definition and measures of variables which are necessary for the fine-grain analysis of team conceptual design activity.

Conceptualising ASE as information processing mechanisms performed by designers to manipulate the design information content in the problem and the solution space requires selection and building on the appropriate definitions that are already available in design and design research literature. In Section 3.1, the definitions of ASE have been adapted to fit with the previously formulated notions of design operations and design entities, and their association with the states of the design content and process, and transitions between these states (Subsection 2.3.2). In addition, the adapted definitions of ASE must be able to embrace and reflect various notions of information processing appearing in Subsections 2.1.2 and 2.2.2. In this way, the micro-level process terms such as “generate”, “clarify”, “simulate”, “formulate”, “decide”, “select”, etc., could all be reduced to three fundamental design information processes, irrespective of the design domain, the type of design problem being solved or the current progress in the development of technical systems. Once defined, ASE correspond to the building blocks of the design process which result from the fine-grain decomposition of team design activity – the so-called “process elements” [228]. These building blocks are then embedded within a single model of team conceptual design activity (Section 3.2) to enable identification and description (Section 3.3) of patterns of analysing, synthesising and evaluating problem- and solution-related design entities.

3.1. Fine-grain decomposition of team design activity

Considering the diversity in interpretation of ASE within the reviewed micro-scale models of the design process, the first step in framing the team conceptual design activity implies adopting (and adapting) clear definitions of analysis, synthesis and evaluation. The definitions reflect the conceptualisation of ASE design operations as fundamental mechanisms for evolving/co-evolving the design entities within both problem and solution space. Furthermore, the team conceptual design activity has been constrained within the domain-independent descriptive model of design by Reymen et al. [183]. In the model, the evolution of the design space (problem and solution) is represented by a set of states, while designing is the activity of transforming one state to another. If designing is decomposed into design operations, then ASE design operations express the transitions between the states of the design space. Figure 3.1 illustrates the sequences of design operations as transitions driving the evolution of the explored design space (change of the state of the product being designed and the state of the design process) while approaching the goal of the design activity.

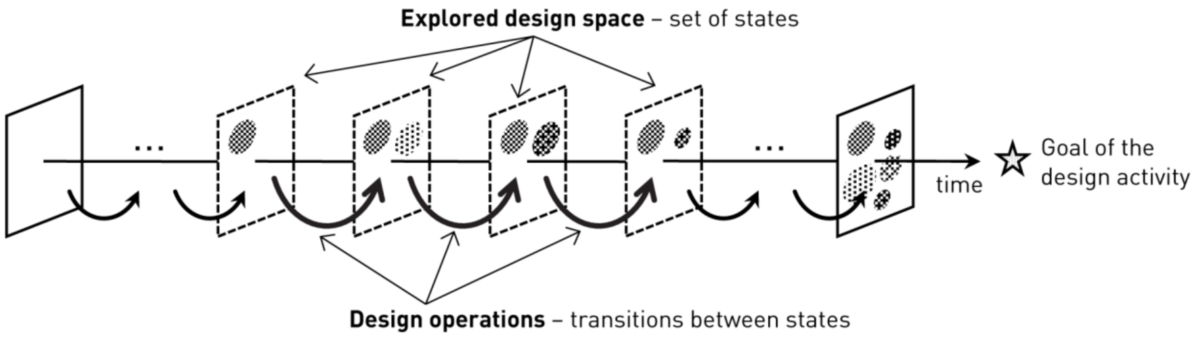

Figure 3.1 Design operations as transitions between states of explored design space (adopted from [183])

In the presented research, the ASE design operations have been defined by adapting the categorisation system for verbal activities in design teams by Casakin and Badke-Schaub [207], since, unlike most of the models, it presumes similar mechanisms for exploration of both the problem and the solution dimensions of the design space. Hereafter, the ASE design operations as transitions between the states of the explored design space have been defined as follows:

– **Analysis** is a state transition resulting in an increased understanding of a particular design entity within the explored design space. When performed in problem space, the purpose of the analysis is to clarify the design problem (needs, requirements, constraints, etc.). The goal of conducting analysis in solution space is to increase the understanding of the proposed solutions to the problem (ideas, concepts, alternatives, etc.). Problem analysis corresponds to "clarification of aspects and questions related to design issues, i.e. user, technical, or budget issues", while solution analysis corresponds to "analysis of a solution idea or part of it", as defined by Casakin and Badke-Schaub [207].

- **Synthesis** is a state transition resulting in the appearance of a new design entity within the explored design space. Solution synthesis corresponds to “stating a new idea or a new solution for a problem or subproblem developing new aspects of an earlier solution idea” [207]. Improvement, refinement and combining of solution entities are also considered as synthesis design operations since the original design entities remain in the solution space, and new derivatives appear. Problem synthesis corresponds to “definitions that are considered in order to structure and define the problem” [207].
- **Evaluation** is a state transition resulting in the assessed utility of a particular design entity within the explored design space. Evaluation of a design entity (in problem or solution space) is performed by addressing a criterion, that is the relevant design entity in the problem space (requirement, constraint, etc.). Two different scenarios of performing evaluation have been identified based on the problem decomposition techniques described by Liikkanen and Perttula [158]. In the first one, the problem space design entities (criteria) are explicitly identified before the execution of evaluation design operation. In the second scenario, the problem entities (criteria) are introduced implicitly within the team at the moment of performing evaluation design operation. Although the goal in both cases is assessing the suitability of a particular design entity (problem or solution), in the second scenario, a new problem entity (criterion) emerges in parallel to the evaluation design operation. McDonnell [229] described the scenario of detecting “misfits” during solution evaluation, which can lead to reframing the problem. In a similar matter, Harvey and Kou [230] explain that the role of evaluation during creative group tasks is not only to provide feedback and make decisions but also to frame the problem. Solution evaluation corresponds to “assessment of a solution idea by focusing on its value and feasibility” as defined by Casakin and Badke-Schaub [207]. They, however, do not propose any verbal activities concerning problem evaluation. Nevertheless, the proposed framework assumes that design entities appearing in the problem space can likewise be evaluated. Hence, problem evaluation is considered as a means of assessing the utility of the new requirements, constraints or subgoals.

The fundamental difference between synthesis and analysis is that as a result of the synthesis design operation a new design entity appears in the explored design space. The fundamental distinction of evaluation design operations is that it also envelops the criterion by which the manipulated design entity is assessed. Figure 3.2 illustrates how ASE design operations act as transitions between the states of the explored design space. The illustration has been simplified by merging the problem and the solution dimensions of the design space. It must be noted that Figure 3.2. illustrates only a single scenario of performing a sequence of ASE design operations and that it does not imply that such sequence is dominant in design.

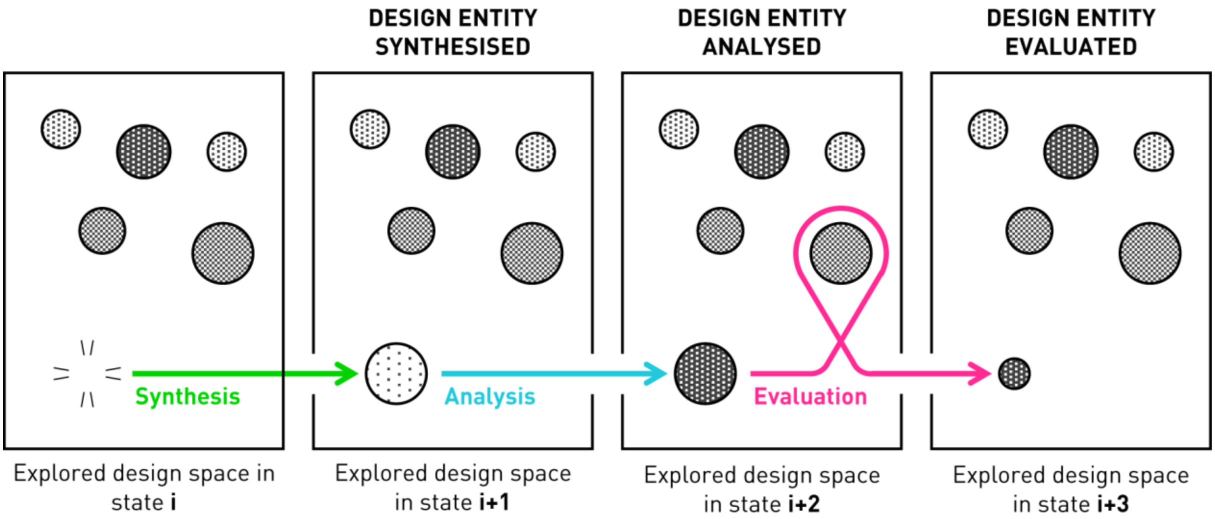

Figure 3.2 Illustration of a state-transition sequence

In state **i**, the explored design space is likely to be populated with both problem and solution entities. If members of the design team perform, for example, a synthesis design operation, a new design entity (problem or solution) is revealed (as a result of the transition from state **i** to state **i+1** in Figure 3.2). The new design entity can be either entirely unrelated to existing ones (new or global searches according to Sarkar and Chakrabarti [210]) or elaboration and improvement of the existing design entities (local and detail searches).

If team members perform analysis design operation, they increase the individual or shared understanding of a design entity (transition from state **i+1** to state **i+2** in Figure 3.2). The aim of analysis can be to avoid misunderstanding [54] or to improve the understanding of certain aspects of design entities (e.g. to determine the behaviour of a solution, as seen by Gero [196]). The better the design entity is understood, the bolder it appears in Figure 3.2 state illustrations.

Finally, as designers progress through conceptual design activity, they require convergent action to narrow down the choices [231], [232]. Designers thus evaluate problems and solutions to distinguish the ones that are reasonable and acceptable. When team members perform evaluation design operation, they asses the utility of a design entity concerning the relevant criteria (the assessed utility of the design entity changes as a result of a transition from state **i+2** to state **i+3** in Figure 3.2). The size of the design entities in Figure 3.2 illustrates the assessed utility.

Formulation of fundamental differences between analysis, synthesis and evaluations and their effect on changing the state of the explored design space enables straightforward mapping of different information processing notions available in the reviewed literature (Subsections 2.1.2, 2.2.2. and 2.3.2). The ability to map information-related processes appearing in other studies is essential for inter-study comparison and discussion of insights resulting from the application of the developed model. An overview of the often-used information-processing notions and the associated ASE design operations is shown in Table 3.1.

Table 3.1 Mapping of various information-processing notions from design literature onto ASE design operations as transitions between states

ANALYSIS	**Analyse** [42], [54], [161], [195], [196], [200], [233], [234]; **Simulate** [195], [200], [235]; **Clarify** [54], [56]; **Acquire** [128]; **Calculate** [235]; **Compare** [235]; **Correct** [56]; **Interpret** [128]; **Understand** [145]; **Read** [236]; **Repeat** [236]; **Request** [236];
SYNTHESIS	**Synthesise** [42], [161], [195], [196]; **Generate** [36], [53], [54], [145], [200], [203], [233], [234], [235]; **Define** [41], [207]; **Elaborate** [233], [236]; **Gather** [131], [234]; **Modify** [203], [236]; **Add** [236]; **Create** [41]; **Compose** [200]; **Formulate** [196]; **Model** [234]; **Patch** [235]; **Propose** [236]; **Refine** [235]; **Redefine** [200]; **Select** [235];
EVALUATION	**Evaluate** [41], [42], [53], [54], [145], [161], [195], [196], [203], [234], [235], [236]; **Decide** [41], [54], [145], [234]; **Select** [53], [203]; **Accept** [54], [235]; **Verify** [233]; **Reject** [235]; **Suspend** [235]; **Qualify** [236]; **Justify** [236]

The mapping of information-related processes was performed based on the definitions given in the literature and relating them to the ASE as illustrated in Figure 3.2, that is, whether an entity is created as a result of that micro-level process (synthesis), whether understanding of an entity has been increased (analysis), or whether the utility of an entity was assessed (evaluation).

3.2. State-transition model of team design activity

The proposed definitions of ASE design operations fit within the framework presented in Figure 3.1 by matching the transitions between the states of the design space. In addition, a micro-scale design process model has been added to the framework to capture the dynamics of these transitions during a team conceptual design activity. According to McMahon [237], fine-grain design process elements such as design operations can be modelled as state transitions. Hence, the dynamics of the micro-scale design process of team conceptual design activities are here described using a state-transition model. The model visualisation is shown in Figure 3.3.

The state nodes in the model represent the states of the design space after ASE design operations have been performed. Once the design entity has been analysed, the state within the model changes to “design entity analysed”, as shown in Figure 3.2 and Figure 3.3. Similarly, the synthesis design operation changes the state to “design entity synthesised” and evaluation to “design entity evaluated”.

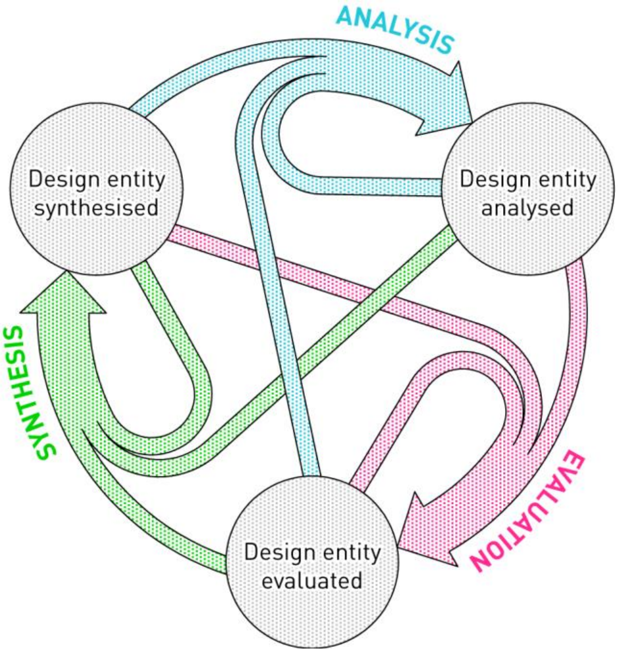

Figure 3.3 State-transition model visualisation illustrating ASE design operations performed within the design space

The model is conceptualised in a way that, when performing an analysis of team design activity, the transitions between the state nodes are assigned with probabilities of being performed by the team and proportions of being performed within a particular period. The probabilities and proportions can be expressed cumulative for the overall activity (based on average probabilities of transitions during the whole activity – see, e.g. Subsections 4.3.1 and 4.3.2), or as they change throughout the activity (see, e.g. Subsection 4.3.3). For example, once team members have synthesised a design entity, they have made a change to the design space. The micro-scale design process is now in the “design entity synthesised” state and the team can carry out further design operations. They can perform analysis, synthesis or evaluation, each with a certain probability assigned within the current state node. If the next step is a synthesis of a new design entity, the transition will return into the same node which will then represent the next state of “design entity synthesised” (now with one new entity). If the team, however, performs analysis or evaluation, the state node changes along with the corresponding transitions. The change in the state node also results with new probabilities for ASE transitions in the following step (e.g. the most probable transition after analysis might be a synthesis, but once synthesis is carried out the most probable transition might then be evaluation).

Rather than having a sequential nature, the model's flexibility allows iterative cycles of a single or several types of design operations. For example, the model can reflect the sequences of ASE design operations driven by divergent (cycles of synthesis) and convergent thinking (cycles of analysis and evaluation) [231], [232], where a single or a pair of design operations dominate. Such descriptions are relevant since new design entities do not appear at a constant pace, nor is every new design entity analysed and evaluated [238].

The model visualised in Figure 3.3 considers design space as one-dimensional (without dividing it to problem and solution space) for the simplicity of representation and clarification. As such, the model consists of three states and nine transitions between these states. Nevertheless, the model can easily be extended to map also ASE transitions within and in-between the problem and the solution space, thus providing additional insight into the co-evolution of these two dimensions. In this way, each transition is divided into four subtypes: two within the spaces (solution to solution and problem to problem), and two in-between the spaces (problem to solution and solution to problem). With these four subtypes of transitions, the model gets more complex as the number of possible transitions rises to 36. The visualisation of ASE transitions in both spaces is presented in Figure 3.4. Additional colour codes have been added to highlight transitions within and in-between the problem and the solution space.

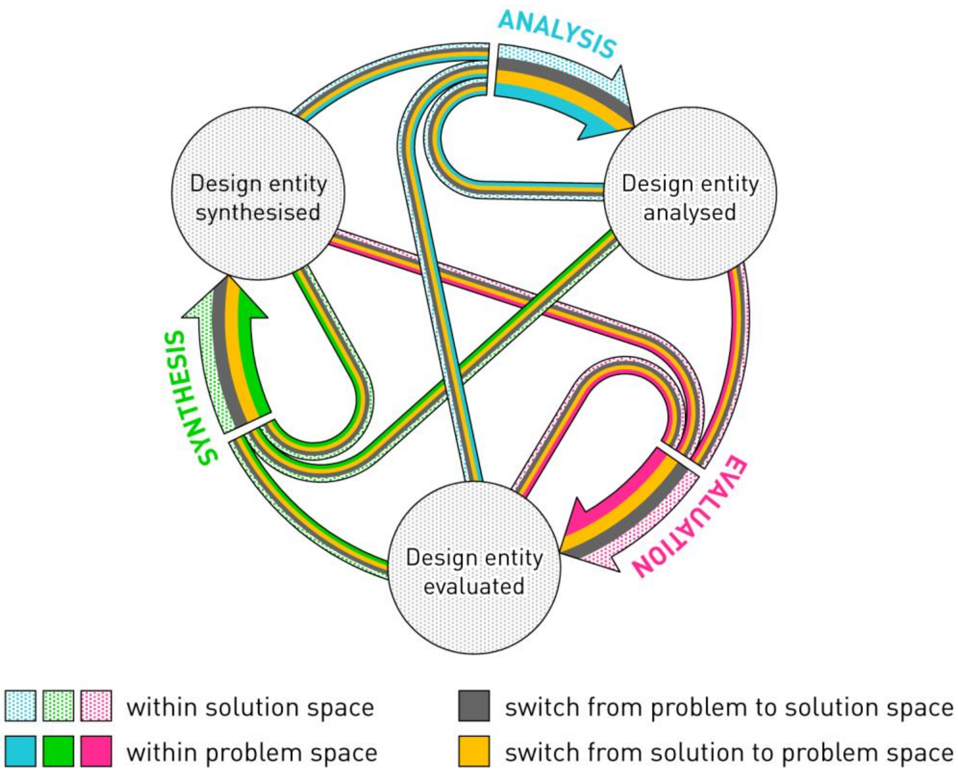

Figure 3.4 Two-dimensional state-transition model visualisation illustrating ASE design operations performed within and in-between problem and the solution space

Transitions within the spaces reflect the evolution of a single space (problem or solution), and transitions in-between the spaces reflect how teams switch from one space to another and thus drive the co-evolution of problems and solutions.

The visualisation of the state-transition model can be further enhanced by assigning thickness to the state transition edges (arrows) based on the proportion of ASE design operations during the team conceptual design activity. In this manner, the relative thickness of a single transition in comparison to other transitions corresponds to the ratio of the matching design operation and all possible design operations during the activity. Experimentally-based examples of visualising the transition proportions are presented as part of the protocol analysis (Chapter 4) and computational, experimental studies (Chapter 6).

3.3. Variables and measures

The theoretical model is intended for capturing design operations by means of experimental studies as well as a support for simulating sequences of design operations during team conceptual design activities. Both purposes require identifying and defining the variables of interest, as well as their measures and a reliable and valid manner of measurement [239]. As shown in the research background (Chapter 2), the majority of fine-grain studies of design activity utilise protocol analysis to decompose the process into small chunks (process elements) [23]. The resulting protocols (instances of process elements) are usually analysed in terms of their duration, frequency and sequences, that is the probabilities of moving from one process element to another (for the most relevant examples, please consult [36], [46], [54], [55], [67], [185], [188], [200], [203], [207], [237], [238]). A similar approach is adopted here, and three dependent sets of variables have been defined as follows:

- **Proportions of design operations:** Instances of ASE design operations within the problem and the solution space are counted and normalised in order to calculate the proportion of each type of design operation in the time span of the team conceptual design activity (or fragment of the activity). Proportions of design operations, which are measured in percentages, provide insight into the general information-processing nature of the investigated activity, in terms of the team's orientation towards analysing, synthesising or evaluating problem and solution entities.
- **Proportions of design operation sequences:** Instances of two or more (depending on the analysis level of detail) consecutive design operations are counted, and the overall

distribution is normalised to calculate the proportions of different combinations of sequences of two or more design operations. Proportions of design operation sequences enable identification of most common state-change patterns exhibited when designing in teams. Proportions of design operation sequences are also measured in percentages.

- **Probabilities of design operation sequences:** Proportions of sequences of two design operations can be transformed into probabilities of moving in-between different types of design operations. Probabilities, again measured in percentages, are essential for both comparing and generating of experimental datasets.

Variables related to proportions of design operations are utilised for measuring and modelling of information processing, whereas the variables related to proportions and probabilities of design operation sequences are used for measuring and modelling the patterns of information processing in teams developing technical systems. It is here argued that the relationship between the proportions of ASE design operations and probabilities of moves between ASE design operations can be statistically modelled, as shown in Chapter 5.

The reliability of the abovementioned measures [239] must be ensured as part of the data collection methodology. In the case of protocol analysis study reported within Chapter 4, the level of reliability is determined by calculating the inter-rater (inter-coder) reliability [185], [240]. The validity of the selected variables [239] and the overall utility of the proposed framework and model are discussed in Chapter 7. The validity is determined qualitatively, based on the aligning of results with other findings from other studies in the design research field. The purpose of the developed theoretical framework and the state-transition model is to capture, describe and simulate both the common and the diverse patterns in proportions and sequences of design operations. Following is the depiction of how different scenarios can be modelled via the developed state-transition model.

3.3.1. Proportions of design operations

As shown in the two-dimensional visualisation of the state-transition model (Figure 3.4), the comprehensive measuring of design operations must include ASE design operation within and in-between the problem and the solution space. Hence, when analysing team design activity, it is necessary to capture the appearance of six basic design operations: problem analysis, problem synthesis, problem evaluation, solution analysis, solution synthesis and solution evaluation. These six types can, if necessary, be aggregated into ASE or problem- and solution-related design operations. Hence, if a team conceptual design activity is decomposed into a string containing *n* instances of design operations, the counted instances can be categorised as shown in Table 3.2.

Table 3.2 Expressions describing numbers of instances and proportions of design operations

	DESIGN OPERATION CATEGORIES	EXPRESSION: Number of instances	EXPRESSION: Proportion
Measured	Problem analysis (PA)	n_{PA}	$p_{PA} = n_{PA} / n$
	Problem synthesis (PS)	n_{PS}	$p_{PS} = n_{PS} / n$
	Problem evaluation (PE)	n_{PE}	$p_{PE} = n_{PE} / n$
	Solution analysis (SA)	n_{SA}	$p_{SA} = n_{SA} / n$
	Solution synthesis (SS)	n_{SS}	$p_{SS} = n_{SS} / n$
	Solution evaluation (SE)	n_{SE}	$p_{SE} = n_{SE} / n$
Aggregated	Analysis (A)	$n_{A} = n_{PA} + n_{SA}$	$p_{A} = n_{A} / n$
	Synthesis (S)	$n_{S} = n_{PS} + n_{SS}$	$p_{S} = n_{S} / n$
	Evaluation (E)	$n_{E} = n_{PE} + n_{SE}$	$p_{E} = n_{E} / n$
	Problem-related (PRO)	$n_{PRO} = n_{PA} + n_{PS} + n_{PE}$	$p_{PRO} = n_{PRO} / n$
	Solution-related (SOL)	$n_{SOL} = n_{SA} + n_{SS} + n_{SE}$	$p_{SOL} = n_{SOL} / n$
	Total	n	$n / n = 100\%$

The symbol *n* with a category index is used to express the measured number of instances of that specific category, and the symbol *p* is used to express the proportions of design operations. As shown in Table 3.2, the proportion of a design operation is expressed as the ratio between the number of instances of that particular operation and the total number of instances of all design operations. Symbolically, the proportion of a design operation p_i can be defined as the number of design operation instances n_i over the total number of instances *n* (Equation 3.1).

$$p_i = \frac{n_i}{n} \qquad \text{(Equation 3.1)}$$

3.3.2. Proportions of design operation sequences

Proportions of sequences of design operations correspond to the proportions of transitions between the states of the explored design space, as conceptualised in Figures 3.1-3.4. A sequence can be defined as two or more consecutive instances of individual design operations. The overall number of sequences within a protocol string depends on the number of instances included in a sequence. For example, a protocol string with *n* instances of design operations contains *n*-1 sequences of two design operations, *n*-2 sequences of three design operations, etc. The proportion of a particular combination of design operations in a sequence equals the ratio of the number of such sequence combinations found in the protocol string and the total number of sequences. An example of possible combinations of sequences of two design operations is shown in Table 3.3. The total number of possible sequence combinations between the six basic design operations is 36, hence only some have been listed in the table. These 36 combinations of moves between two design operations can be aggregated into 9 combinations of moves between analysis, synthesis and evaluation and 4 combinations of moves in-between the problem- and the solution-related operations.

Table 3.3 Expressions describing numbers of instances and proportions of different combinations of two consecutive design operations

	EXPRESSION	
	Number of instances	**Proportion**
Measured	$n_{PA,PA}$ (from problem analysis to problem analysis)	$p_{PA,PA} = n_{PA,PA} / (n-1)$
	$n_{PA,PS}$	$p_{PA,PS} = n_{PA,PS} / (n-1)$
	$n_{PA,PE}$	$p_{PA,PE} = n_{PA,PE} / (n-1)$
	$n_{PA,SA}$	$p_{PA,SA} = n_{PA,SA} / (n-1)$
	$n_{PA,SS}$	$p_{PA,SS} = n_{PA,SS} / (n-1)$
	$n_{PA,SE}$	$p_{PA,SE} = n_{PA,SE} / (n-1)$
	$n_{PS,PA}$	$p_{PS,PA} = n_{PS,PA} / (n-1)$
	$n_{PS,PS}$	$p_{PS,PS} = n_{PS,PS} / (n-1)$
	$n_{PS,PE}$	$p_{PS,PE} = n_{PS,PE} / (n-1)$
	⋮	
Aggregated	$n_{A,A} = n_{PA,PA} + n_{PA,SA} + n_{SA,PA} + n_{SA,SA}$	$p_{A,A} = n_{A,A} / (n-1)$
	$n_{A,S} = n_{PA,PS} + n_{PA,SS} + n_{SA,PS} + n_{SA,SS}$	$p_{A,S} = n_{A,S} / (n-1)$
	$n_{A,E} = n_{PA,PE} + n_{PA,SE} + n_{SA,PE} + n_{SA,SE}$	$p_{A,E} = n_{A,E} / (n-1)$
	$n_{S,A} = n_{PS,PA} + n_{PS,SA} + n_{SS,PA} + n_{SS,SA}$	$p_{S,A} = n_{S,A} / (n-1)$
	$n_{S,S} = n_{PS,PS} + n_{PS,SS} + n_{SS,PS} + n_{SS,SS}$	$p_{S,S} = n_{S,S} / (n-1)$
	$n_{S,E} = n_{PS,PE} + n_{PS,SE} + n_{SS,PE} + n_{SS,SE}$	$p_{S,E} = n_{S,E} / (n-1)$
	$n_{E,A} = n_{PE,PA} + n_{PE,SA} + n_{SE,PA} + n_{SE,SA}$	$p_{E,A} = n_{E,A} / (n-1)$
	$n_{E,S} = n_{PE,PS} + n_{PE,SS} + n_{SE,PS} + n_{SE,SS}$	$p_{E,S} = n_{E,S} / (n-1)$
	$n_{E,E} = n_{PE,PE} + n_{PE,SE} + n_{SE,PE} + n_{SE,SE}$	$p_{E,E} = n_{E,E} / (n-1)$
	$n_{PRO,PRO} = n_{PA,PA} + n_{PA,PS} + n_{PA,PE} + n_{PS,PA} + n_{PS,PS} + n_{PS,PE} + n_{PE,PA} + n_{PE,PS} + n_{PE,PE}$	$p_{PRO,PRO} = n_{PRO,PRO} / (n-1)$
	$n_{PRO,SOL} = n_{PA,SA} + n_{PA,SS} + n_{PA,SE} + n_{PS,SA} + n_{PS,SS} + n_{PS,SE} + n_{PE,SA} + n_{PE,SS} + n_{PE,SE}$	$p_{PRO,SOL} = n_{PRO,SOL} / (n-1)$
	$n_{SOL,PRO} = n_{SA,PA} + n_{SA,PS} + n_{SA,PE} + n_{SS,PA} + n_{SS,PS} + n_{SS,PE} + n_{SE,PA} + n_{SE,PS} + n_{SE,PE}$	$p_{SOL,PRO} = n_{SOL,PRO} / (n-1)$
	$n_{SOL,SOL} = n_{SA,SA} + n_{SA,SS} + n_{SA,SE} + n_{SS,SA} + n_{SS,SS} + n_{SS,SE} + n_{SE,SA} + n_{SE,SS} + n_{SE,SE}$	$p_{SOL,SOL} = n_{SOL,SOL} / (n-1)$

The n symbol and the assigned transition indexes are used to express the measured number of design operation sequences, whereas p is used to express their proportions. Symbolically, the proportion of moves between two consecutive design operations $p_{i,j}$ can be defined as the number of counted sequences of these two design operations $n_{i,j}$ over the total number of sequences of two design operations n-1 (Equation 3.2). Similarly, the proportion of moves between three consecutive design operations $p_{i,j,k}$ equals the number of three design operations $n_{i,j,k}$ over the total number of sequences of three design operations n-2 (Equation 3.3).

$$p_{i,j} = \frac{n_{i,j}}{n - 1} \quad \text{(Equation 3.2)}$$

$$p_{i,j,k} = \frac{n_{i,j,k}}{n - 2} \quad \text{(Equation 3.3)}$$

Experimental studies (Chapters 4 and 6) have shown that analysing sequences of more than three consecutive design operations provides no significant benefits, primarily due to a small number of instances for every possible combination appearing in a team activity time span.

3.3.3. Probabilities of design operation sequences

The probabilities of one design operation following another design operation, i.e. one state transition following another state transition have been interpreted as probability matrices in Markov processes respectively [241]. The probability matrix (Markov matrix) is a right stochastic matrix – a square matrix used to describe the probabilities of moving from one element in the matrix (in this case a design operation) to all other elements [241]. It is important to note that the common term used to link the elements of a probability matrix is a "transition". However, to reduce the ambiguity when discussing transitions between design operations (transitions of transitions in the proposed model), this term has been replaced with "moves".

First, the total number of moves between pairs of design operations must be counted and entered into the corresponding cells of the matrix. The probability matrix is then computed by normalising the matrix rows (the sum of values in each row of a right stochastic matrix is 1). The matrix includes the probabilities of design operation to appear, given the previous design operations. Symbolically, the probability of a design operation j to appear after design operation i can be formulated as the ratio of the proportion of moves between design operations p_{ij} over the proportion of the first design operation p_i (Equation 3.4).

$$Pr(j \mid i) = \frac{p_{i,j}}{p_i} \quad \text{(Equation 3.4)}$$

The transitions matrices can then be formulated as shown in the tables below. Probability matrix shown in Table 3.4 involves the probabilities of moves between ASE design operations within and in-between the two dimensions of the explore design space, whereas the matrices shown in Table 3.5 aggregate these probabilities into probabilities of moves in-between analysis, synthesis and evaluation (left), and problem- and solution-related design operations (right).

Table 3.4 Probabilities of moves between two ASE design operations within and in-between problem and solution space, given the previous design operation

FROM ↓ **TO →**	**PA**	**PS**	**PE**	**SA**	**SS**	**SE**
Problem analysis (PA)	$\frac{p_{PA,PA}}{p_{PA}}$	$\frac{p_{PA,PS}}{p_{PA}}$	$\frac{p_{PA,PE}}{p_{PA}}$	$\frac{p_{PA,SA}}{p_{PA}}$	$\frac{p_{PA,SS}}{p_{PA}}$	$\frac{p_{PA,SE}}{p_{PA}}$
Problem synthesis (PS)	$\frac{p_{PS,PA}}{p_{PS}}$	$\frac{p_{PS,PS}}{p_{PS}}$	$\frac{p_{PS,PE}}{p_{PS}}$	$\frac{p_{PS,SA}}{p_{PS}}$	$\frac{p_{PS,SS}}{p_{PS}}$	$\frac{p_{PS,SE}}{p_{PS}}$
Problem evaluation (PE)	$\frac{p_{PE,PA}}{p_{PE}}$	$\frac{p_{PE,PS}}{p_{PE}}$	$\frac{p_{PE,PE}}{p_{PE}}$	$\frac{p_{PE,SA}}{p_{PE}}$	$\frac{p_{PE,SS}}{p_{PE}}$	$\frac{p_{PE,SE}}{p_{PE}}$
Solution analysis (SA)	$\frac{p_{SA,PA}}{p_{SA}}$	$\frac{p_{SA,PS}}{p_{SA}}$	$\frac{p_{SA,PE}}{p_{SA}}$	$\frac{p_{SA,SA}}{p_{SA}}$	$\frac{p_{SA,SS}}{p_{SA}}$	$\frac{p_{SA,SE}}{p_{SA}}$
Solution synthesis (SS)	$\frac{p_{SS,PA}}{p_{SS}}$	$\frac{p_{SS,PS}}{p_{SS}}$	$\frac{p_{SS,PE}}{p_{SS}}$	$\frac{p_{SS,SA}}{p_{SS}}$	$\frac{p_{SS,SS}}{p_{SS}}$	$\frac{p_{SS,SE}}{p_{SS}}$
Solution evaluation (SE)	$\frac{p_{SE,PA}}{p_{SE}}$	$\frac{p_{SE,PS}}{p_{SE}}$	$\frac{p_{SE,PE}}{p_{SE}}$	$\frac{p_{SE,SA}}{p_{SE}}$	$\frac{p_{SE,SS}}{p_{SE}}$	$\frac{p_{SE,SE}}{p_{SE}}$

Table 3.5 Probabilities of moves between two design operations aggregated to ASE (left) and problem- and solution-related design operations (right)

FROM ↓ **TO →**	**A**	**S**	**E**
Analysis (A)	$\frac{p_{A,A}}{p_{A}}$	$\frac{p_{A,S}}{p_{A}}$	$\frac{p_{A,E}}{p_{A}}$
Synthesis (S)	$\frac{p_{S,A}}{p_{S}}$	$\frac{p_{S,S}}{p_{S}}$	$\frac{p_{S,E}}{p_{S}}$
Evaluation (E)	$\frac{p_{E,A}}{p_{E}}$	$\frac{p_{E,S}}{p_{E}}$	$\frac{p_{E,E}}{p_{E}}$

FROM ↓ **TO →**	**PRO**	**SOL**
Problem-related (PRO)	$\frac{p_{PRO,PRO}}{p_{PRO}}$	$\frac{p_{PRO,SOL}}{p_{PRO}}$
Solution-related (SOL)	$\frac{p_{SOL,PRO}}{p_{SOL}}$	$\frac{p_{SOL,SOL}}{p_{SOL}}$

Variables describing the proportions of individual design operations and probabilities of moves from one design operation to another are not independent. The probabilities of moves between two design operations are inherited from proportions of individual design operations. For example, the more analysis-intensive an activity is, the higher the probability of moves from either analysis, synthesis or evaluation towards analysis. Nevertheless, the precise relationship between these variables can only be hypothesised at this point. Linear regression modelling using experimental data sets is needed to determine the type of dependency (linear, polynomial) and the coefficient involved (consult Chapter 5 for more details).

3.3.4. Proportion visualisation

In order to characterise the gravitation of activity towards the analysed, synthesised and evaluated states, the overall state-transition model visualisation can be simplified as a triangular representation of the ASE proportions, as shown in Figure 3.5. The triangular proportion visualisation has been colour-coded to emphasise the prevalent design operation type. Thus, activities characterised as analytic gravitate towards the upper right corner of the triangular proportion visualisation. Moreover, synthesis-intensive activities gravitate towards the top left, and the evaluation-intensive activities gravitate towards the bottom corner of the triangular proportion visualisation.

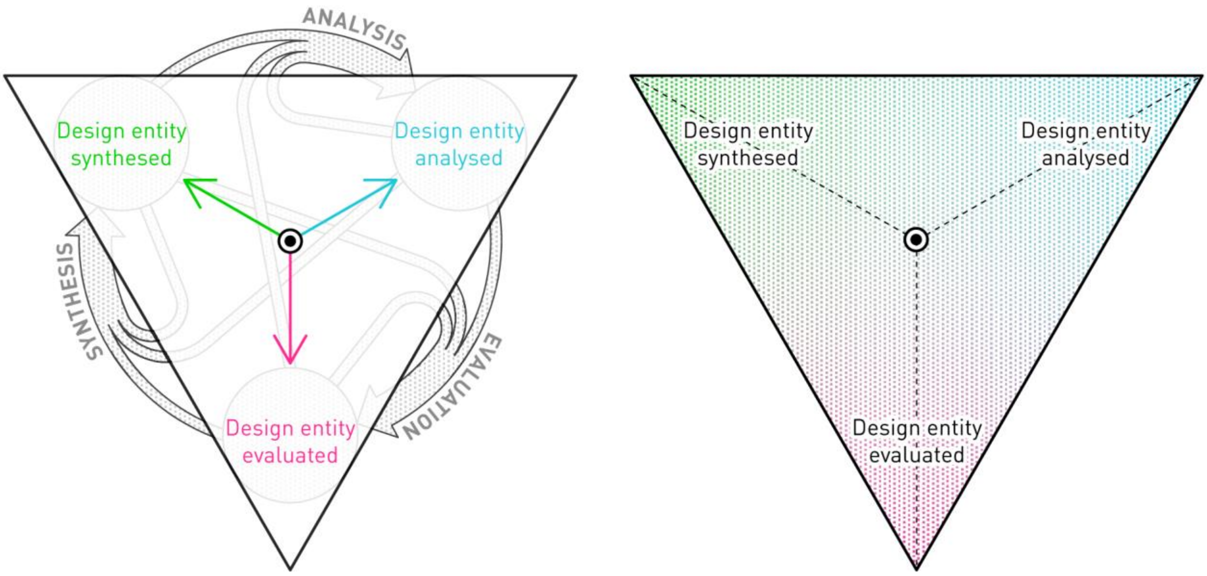

Figure 3.5 Simplified triangular visualisation of design operation proportions in-between different states of design entity manipulation (left); and colour-coded visualisation of prevailing design operations (right)

Since the proportions of ASE make up 100% of all transitions between the states of the design space, only two measures are needed to characterise an activity. If the triangular proportion visualisation is utilised, the two measures are embedded in the vector which is anchored in the centre of the triangle (Figure 3.6). The measures correspond to the vector's endpoint distance from the triangle centre of gravity (vector length r) and the direction of the vector (vector direction angle δ), as shown in Figure 3.6. If the distance R from the centre of gravity to the corners of the triangle is conceptualised as equal to 1 (or 100%), then the vector length r ranges from 0 to a maximum of 1 in the triangle corners, whereas the vector direction δ can be any angle. Furthermore, if the angle δ is defined clockwise from the vertical axis, as shown in Figure 3.6, the relations between the triangular visualisation variables and the proportions of ASE design operations can be defined as shown in Equations 3.5, 3.6 and 3.7.

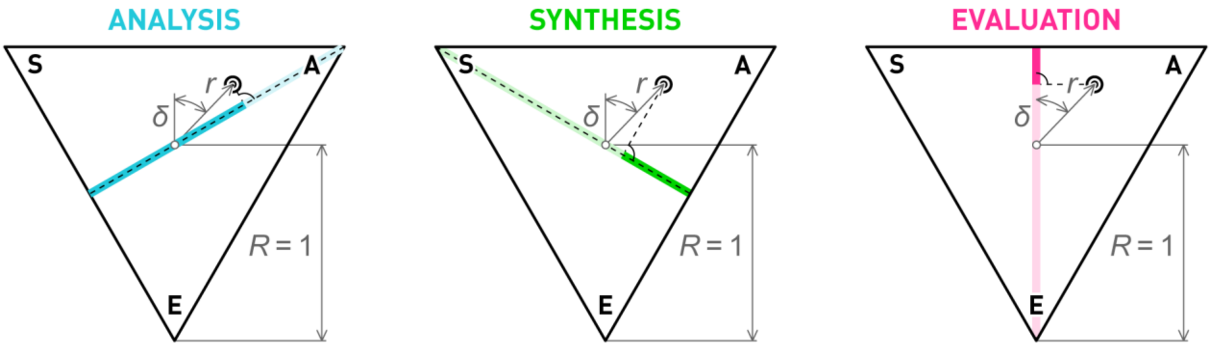

Figure 3.6 Triangular proportion visualisation of ASE design operations using two visualisation variables – distance from the centre of gravity *r* and angle *δ*

Equations 3.5-3.7 reveal that, in the case where the vector length is zero, the proportion of all three design operations is equal to 1/3.

$$p_A = \frac{1}{3} + \frac{2}{3} \cdot r \cdot \cos(60° - \delta) \quad \text{(Equation 3.5)}$$

$$p_S = \frac{1}{3} - \frac{2}{3} \cdot r \cdot \sin(\delta - 30°) \quad \text{(Equation 3.6)}$$

$$p_E = \frac{1}{3} - \frac{2}{3} \cdot r \cdot \cos(\delta) \quad \text{(Equation 3.7)}$$

The proposed visualisation does not only enable intuitive and straightforward characterisation activities' nature in terms of ASE but can also be used to describe the change in ASE proportions as a function of time passed within either a single activity or a set of activities performed by the design team. An example of such visualisation is shown in Figure 3.7.

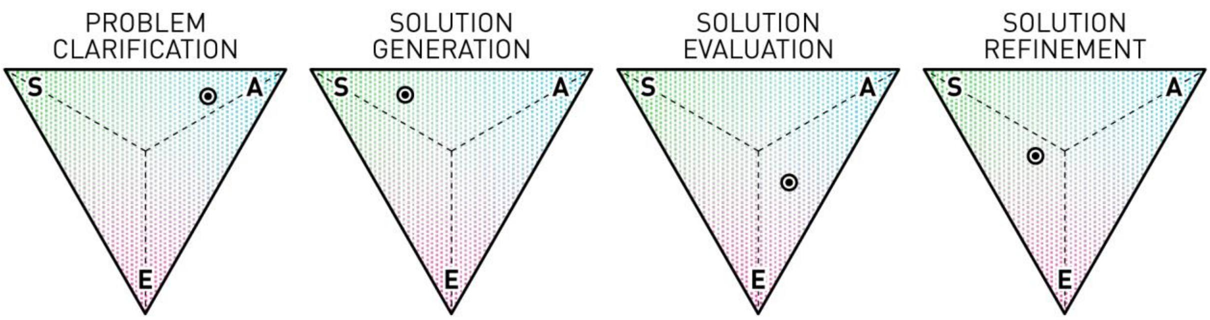

Figure 3.7 An example of changes in ASE proportions during a conceptual design task

The example in Figure 3.7 illustrates the steps of solving a conceptual design task, inspired by the descriptions of the conceptual design stage provided in Table 2.5. The team first clarifies the given problem (analysis intensive), then generates a solution alternative (synthesis), before evaluating the alternative (analysis and evaluation). Finally, the selected solution is refined (evaluation and synthesis).

Another example of visualising different proportions of ASE and illustrating the hypothesised effect of these proportions on the proportions of nine transitions between the three states of the explored design space is shown in Figure 3.8. The proportions of moves between design operations have been visualised by adjusting the thickness of state-transition edges (arrows).

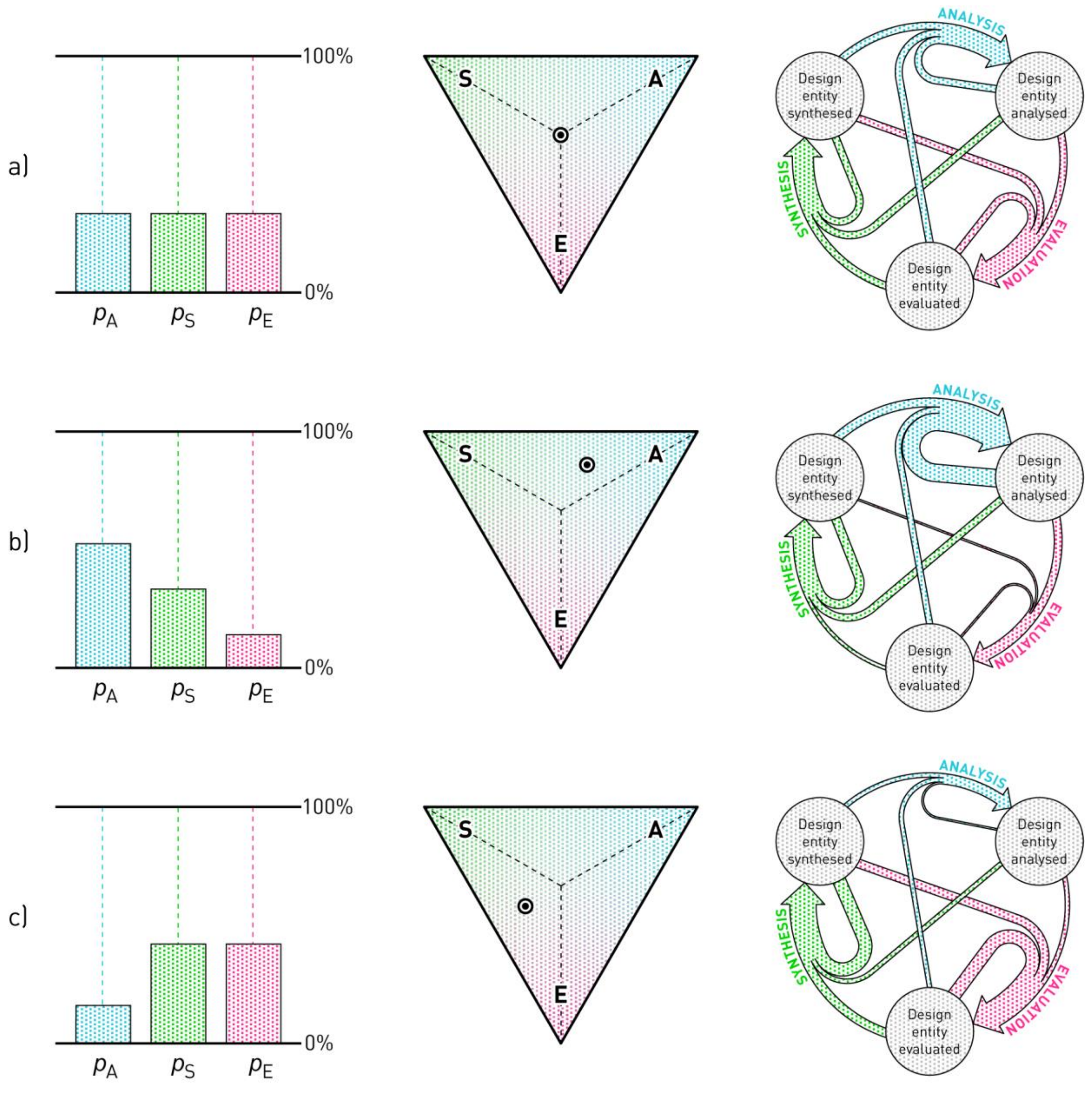

Figure 3.8 Examples of different ASE proportions, their gravitation toward design entity states and visualisation of state transitions: a) $p_A=p_S=p_E$; b) $p_A>p_S>p_E$; c) $p_S=p_E>p_A$

A more detailed analysis of proportions can further be performed by assigning ASE design operations to the two dimensions of the design space. The one-dimensional analysis of proportions and moves between design operations can be analogously expanded to the problem and the solution space. Hence, the number of proportion variables doubles, as ASE can be measured within both the problem and the solution space. Moreover, the number of possible moves between pairs of ASE design operations within and in-between the problem and the solution space rises to 36 (as shown in Figure 3.4 and Table 3.4). The ASE-related nature of design activities can then be characterised for both spaces. However, it is yet to be investigated if the problem and solution space are likely to exhibit similar proportions and sequences of ASE design operations.

The following three chapters focus on application and further prescriptive development of here presented theoretical framework, particularly concerning the state-transition model and the associated visualisations. Protocol analysis study (Chapter 4) utilises the framework for capturing, analysing and visualising information processing during team ideation and concept review activities. The results of the analysis have then used the development of a mathematical model (Chapter 5), that is for modelling the relationships between proportions of individual design operations and the probability of moves in-between different types of design operations. The mathematically formalised relationships are then used to simulate sequences of design operations during team conceptual design in the context of innovative and adaptive design projects (Chapter 6).

4. PROTOCOL ANALYSIS STUDY

The fourth chapter reports on the first experimental study of team ideation and concept review activities. First, the experiment setup and the obtained experimental data sets are described. Then a coding scheme is developed, and the verbal protocol analysis method is employed to capture instances of design operations, as defined in the previous chapter. Finally, the results on proportions and probabilities of design operations and their sequences are presented, and the two activities are compared in order to identify statistically significant differences between team ideation and concept review.

Guided by the studies investigating fine-grain patterns of information processing in team design activity (Section 2.3), the first experimental study has been conducted in the form of verbal protocol analysis. There are several reasons for selecting verbal protocol analysis as the principal means of investigating team conceptual design activity. Firstly, conceptual design communication in design teams is primarily verbal [50], [98]. Secondly, the concern regarding the validity of verbalisations in teamwork is irrelevant, since it is natural for team members to verbally communicate when working together, making verbal data an authentic reflection of real-time thinking in design teams [28]. Thirdly, since the presented research focuses on the observable design operations, the segments when designing is not (or cannot be) verbalised are not documented and modelled as observable information-processing steps in the design process. As a “third-party observing”, protocol analysis can be scientific, independent and relatively objective if it is used to detect the observable aspects of designing [70], [242].

In the light of the research questions RQ2 and RQ3 (Section 2.4), and the developed theoretical framework (Chapter 3), the aim of utilising protocol analysis has been the identification of fine-grain patterns of ASE design operations during team ideation and concept review activities. Methodologically, the protocol analysis study consisted of three main stages: (1) identifying, obtaining and describing the experimental data set, (2) segmentation and coding, and (3) data analysis and interpretation of the results. The first step was focused on the gathering of experimental data (Section 4.1), namely defining criteria for selecting the appropriate recordings of team conceptual design sessions. In the second step, the recordings of conceptual design sessions were segmented and coded (Section 4.2). The coding scheme for verbal protocol analysis was defined accordingly to the theoretical framework of team conceptual design activity established in step one. Lastly, in the final step, the protocol data were analysed and discussed (Section 4.3).

4.1. Experimental dataset

Several features were considered when identifying the appropriate experimental data set. The recorded experiment sessions should have been collaborative activities, where teams engage in tasks of conceptual design nature. The duration of the task execution should have been relatively short (e.g. no more than two hours) due to the use of protocol analysis method, but long enough to collect a sufficient number of data points. Furthermore, teams should have participated in two different types of activities within the conceptual design stage, to address the research question RQ3.

Video recordings of the two types of team conceptual design activities were obtained from previously conducted studies by Cash et al. [243]. The decision to use existing raw recording data provided several benefits. First, the received data set meets the study requirements, so conducting new experiments could have been avoided. Second, the data set results from a rigorously designed experiment and has already passed several cycles of thorough examination, peer review and publication. Third, studies that used the same raw data set provide additional insights into the design process and offer the potential of coupling the results.

The original experiment structure consisted of four sessions, two of which were team activities – ideation and concept review. The other two activities of the experiment were performed by designers individually and are thus not in focus of here presented protocol analysis study. Nevertheless, to provide context for the team sessions, the complete experiment structure is introduced. The overall experiment structure is aligned with the tasks that designers are involved in during the conceptual design stage, as shown in Table 2.4. Hence, in each experiment session, the participants were given a task – a formulation of a design problem to be solved, aiming at the observation and the examination of the design process [244].

The participants were first engaged in individual information seeking task, particularly for feasibility level technical information on camera mounting devices. This individual task was followed by a collaborative ideation activity, in which participants were grouped into teams of three and given a design brief to deliver concept ideas for mounting a camera on a balloon. After the team sessions, participants have again worked on individual design tasks to develop a single, elaborated concept. Finally, the teams met again to review and refine the concepts

[243]. Combining individual and team activity is essential in engineering design. Ulrich and Eppinger explain that team members should spend at least some of their concept generation time working alone, whereas team activities are critical for building consensus, communicating information and refining concepts [120]. Moreover, the practice of divergent ideation, followed by elaboration and integration of ideas, and completed by narrowing and refining ideas is not unique to design, as similar progress can be found across creative group task processes [230].

A total of twelve participants were randomly allocated to four teams. The teams were composed of mechanical engineering students selected from a final year product design and development course. Each participant had an average of 10 months of industrial experience and four years of academic training background at the time of the experiment. For more information on the teams, please consult Cash et al. [243] and Cash and Maier [245].

4.1.1. Ideation activity

During the ideation activity, the teams had 50 minutes to generate as many viable ideas as possible for a camera-mounting concept hanged under a helium balloon. The ideation task brief is shown in Figure 4.1. Before the session, team members have performed a search for information that might help to develop a universal camera mount for an aerial vehicle. The concept should have been capable of mounting any camera and orienting it to any point in a hemispherical region. The solution must have been operated remotely. Teams could have recorded their ideas on the whiteboard and sheets of paper. The protocol was based on the participants' natural conversational acts (without imposing any verbalisation requirements), to reduce the effects of observation. For more information, please consult Cash et al. [243].

4.1.2. Concept review activity

Prior to the concept review activity, team members worked individually on developing detailed concepts of the camera mount. They elaborated their concept based on the additional information on available manufacturing and assembly technologies. Team compositions for the concept review activity were the same as for the ideation activity. During the concept review activity, the teams had 50 minutes to review concepts they developed and elaborated during the individual concept generation task. They were instructed to select and develop one, or a combination of concepts and refine them into a final concept solution. The concept review task brief is shown in Figure 4.2. More information can be found in Cash et al. [243].

During this task we would like you to brainstorm ideas to fulfil the following brief. The aim of this task is to generate as many viable ideas as possible within the time available. Please record these ideas on the white-board as they occur but feel free to make additional notes as necessary.

Using the specification provided, develop a variety of concepts capable of mounting any camera, while slung under a helium balloon. The mount must be capable of orientating the camera to any point in a hemi-spherical region underneath the balloon, and must be operated remotely.

Specification:

Total mass of camera and mount	6 kg (must take a range of cameras within weight limits)
Cost (cost price) of the mount	£75
Operational life (per charge)	1.5 hours
Speed of operation – 360º pan	maximum 30 s minimum 10 s
Type of control	via laptop
Range of controller	100 m
Range of rotation	360º by 180º
Volumetric size	200 x 200 x 150 mm
Balloon connection	flexible
Balloon size	spherical

The design for the balloon has already been finalised, and is tolerant of any connection or interface with the camera mount. Although you should try to minimise motion in the mount where possible, you do not need to consider vibration.

Balloon configuration pictures:

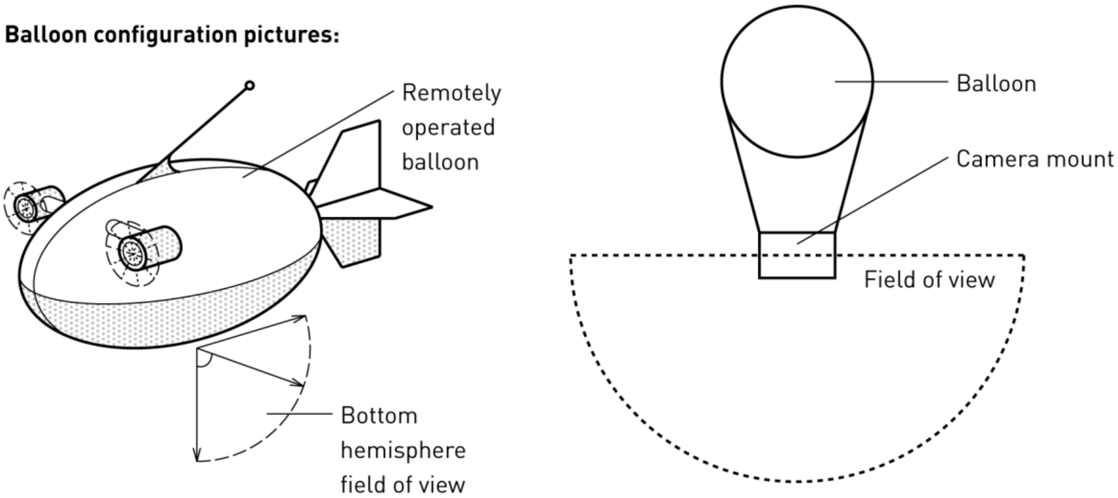

Figure 4.1 Ideation activity task brief (adopted from [246])

During this task we would like you to review your designs (as developed in the previous task). The aim of this task is to select and develop one (or a combination of ideas) into a final concept to be taken forward to production. Please see the following: With your colleagues, and using your developed concepts, select and further develop a single, final concept that best fulfils the brief and specification. Please record this final concept on a single sheet of A3 paper.

Figure 4.2 Concept review activity task brief (adopted from [246])

4.2. Protocol analysis

Protocol coding was conducted using the ELAN software [247] for video annotation (software interface is shown in Figure 4.3). The data set which has been imported within the annotation software consists of 3 separate video recording files per session. Two cameras were oriented towards the experiment participants (team members), whereas the third one was pointing at the whiteboard. Experiment participants communicated in English which is also their native language. A coding scheme has been developed through several iterations of familiarisation with the video recording data sets. Once finalised, the coding scheme was imported to the annotation software. The final coding scheme and the coding process are explained in this section.

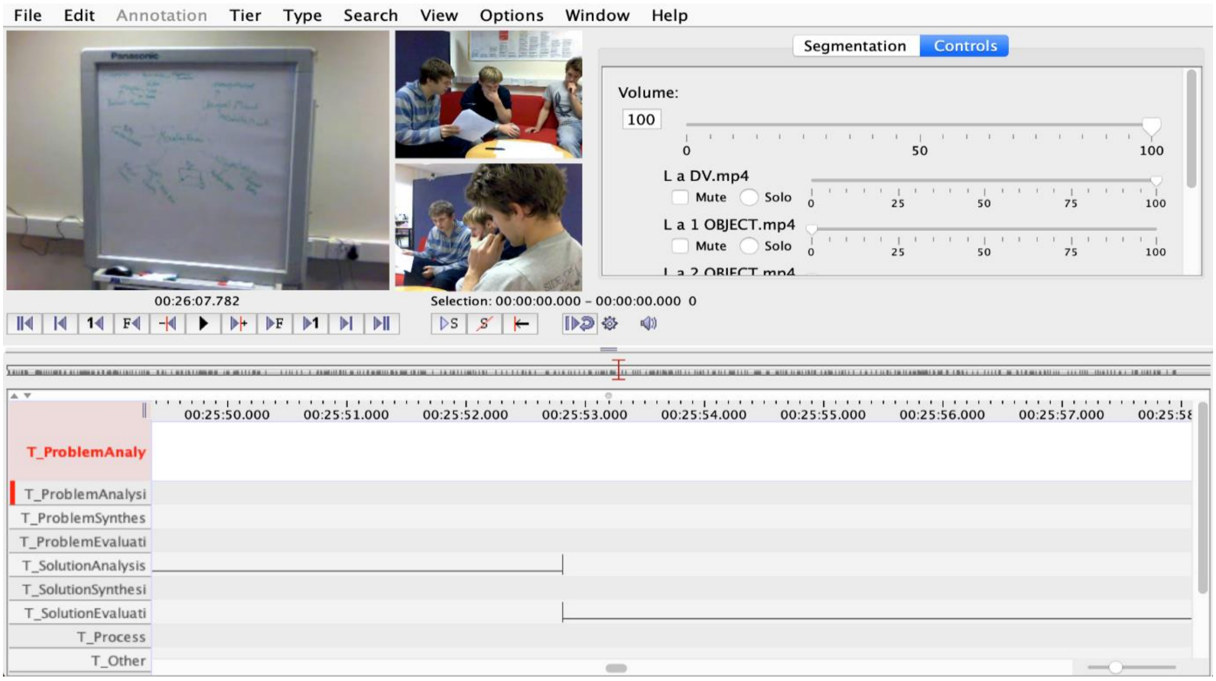

Figure 4.3 Interface of ELAN video annotation software [247] used for protocol coding

4.2.1. Coding scheme

As part of the verbal protocol analysis, the recorded team conversations have been transcribed and parsed into coded segments, which were then treated as units of analysis [83], [232]. The transcription process helped to familiarise with the data and to develop and refine the instructions for coding before performing the final segmentation and coding step. Moreover, two additional codes, "process" and "other", have been recognised and added to the coding scheme in order to capture communicative acts which are not related to the design space. Although the two additional codes have not been considered in here presented analyses (see

Section 4.3), they were included in the coding scheme for the convenience of future research using the same experimental data set. The final coding scheme and the results of the inter-rated reliability test (κ_a – explained in detail within the following subsection) are shown in Table 4.1.

The core of the scheme consists of six codes that match the adopted definitions (Chapter 3) of ASE design operations in the problem space (problem analysis, problem synthesis, problem evaluation) and the solution space (solution analysis, solution synthesis, solution evaluation). The "process" code is used for discussions concerning the action plan within the session. Detailed process-specific codes were not considered as only a small amount of process-related discussion has been identified. Clear instructions about the design task have been given before sessions start, and there was no need for teams to realign the process often. All remaining communicative acts such as any off-topic discussion, naming unrelated facts and joking were coded as "other". An example of a segmented and coded transcript is shown in Table 4.2.

Table 4.1 The coding scheme for annotating segments of design team conversation

CODE	DESCRIPTION	CODERS' RELIABILITY (κ_a)
pa: problem analysis	Communicative acts concerning the understanding of problem entities, such as requirements, constraints, specification, user needs, use scenarios, criteria or functions	0.72
ps: problem synthesis	Communicative acts resulting in the appearance of new problem entities	0.78
pe: problem evaluation	Communicative acts concerning the utility assessment of problem entities	0.78
sa: solution analysis	Communicative acts concerning the understanding of solution entities, such as ideas and concept solutions	0.70
ss: solution synthesis	Communicative acts resulting in the appearance of new solution entities	0.79
se: solution evaluation	Communicative acts concerning the utility assessment of solution entities	0.78
proc: process	Communicative acts concerning the process of the activity (where to start, how to proceed, etc.)	0.93
o: other	Communicative acts that cannot be annotated with the codes defined above (unrelated facts, joking, off-topic discussion)	0.95

The developed coding scheme was applied to the transcripts of the experiment sessions. The segments were coded following the "one-segment-with-one-code" principle (see [55]). Each segment was assigned with only one of the eight codes based on the coder's critical judgment of recognising ASE design operations as defined in the previous section. Although the situations in which more than one designer was talking were rare, these segments were coded based on the statement that was more dominant and to which the discussion continued.

4.2.2. Inter-rater reliability

The protocols were coded by the primary researcher and a trained coder who was not involved in the development of the framework. The first (primary) coder coded the entire 50 minutes of the eight experiment sessions. The second (reliability) coder coded random 10 minutes intervals (20% of total session duration) of each experiment session, in order to satisfy the proportion needed for the calculation of inter-rater reliability, as suggested by Klonek et al. [248]. Similar approaches to reliability analysis in research of design teams can be seen in the studies of Deken et al. [63], Wiltschnig et al. [67], Eris et al. [58] and Snider et al. [249].

Table 4.2 An excerpt of segmenting and coding of experiment transcripts

TIME	PARTICIPANT	SEGMENT TRANSCRIPT	CODE
7:34	P1	[weight restriction concerning the cameras is discussed] *So, we are saying from 200 grams to 3 kilograms...*	ps (new constraint)
7:49	P3	*You then might not be able to attach the full-frame camera...*	pe (constraint evaluated)
7:53	P2	*I think it will be more reasonable to restrict the weight it would lift to a range of decent cameras.*	ps (constraint modified)
8:04	P1	*What about the attachment of the camera?* [requirement introduced earlier in the session]	pa (requirement analysed)
8:10	P1	*The standard camera attachment is this quarter inch threaded screw...*	ss (solution proposed)
8:20	P2	*Screw...? The tripod mount?*	sa (solution clarified)
8:22	P1	*Yes.*	
8:23	P2	*Yeah, that's the thing. Everything has that one... From little compacts right to the big DSLRs*	se (solution evaluated)
8:35	P1	[writing the solution proposal on the whiteboard] *So that is very standard...*	

Since the presented verbal protocol analysis aims to investigate distribution and sequences of design operations, the outputs of the coding are depicted as strings of codes, which are defined by Quera et al. [250] as event sequences. During the coding process, the coders need to identify the events (instances) of analysis, synthesis and evaluation within the problem and the solution space. For this reason, the strings of protocol codes produced by two independent coders may differ in length; that is, the number of coded instances and their alignment are likely to be different. As a consequence, the calculation of Cohen's kappa – the typical approach to assessing the inter-rater reliability – cannot be performed, as it is not clear how the two event sequences can be aligned. A procedure by Quera et al. [250] was utilised to calculate the event-based interpretation of kappa: the event alignment kappa (κ_a).

GSEQ software (see, e.g. [248]) was used to compute the event alignment kappa for each code. Both the overall event alignment kappa value (κ_a=0.71) and the event alignment kappa values for particular codes (reported in Table 4.1) indicate substantial agreement between the two coders. In comparison with other experimental studies in design research (see, e.g. [46], [67], [187]), the agreement has been assessed as adequate for ensuring research rigour. Once the inter-rater reliability was assessed, all of the identified conflicts have been resolved, and the final event sequences were agreed.

4.3. Protocol analysis results

The results are presented in three parts. The first part reveals the frequencies of segments assigned with different types of codes during the two experimental sessions, with a particular focus on segments related to design operations. In the second part, the transitions between the coded segments are analysed to identify the sequences of design operations. The ideation and concept review experiment sessions are first examined separately and are then compared to determine the significant differences. Finally, the third part reports on the analysis of change in design operation proportions and sequences throughout the sessions. From here on, the experiment sessions will be referred to as ideation and concept review activities.

On average, 333 codes have been coded per team during the ideation activity, and 313 per team during the concept review activity. The discussion related to the problem and the solution space accounts on average for 293 segments per team during the ideation (85-90% of all segments), and for 280 segments per team during the concept review activity (87-92%). The process-related conversation has averaged at 6% during ideation, and at 5% during concept review, and other communicative acts between 5% and 6%. The absolute frequencies of each coded segments and their aggregation to ASE design operations and problem-solution spaces during both activities are available in Table 4.3.

Table 4.3 Absolute frequencies of instances of protocol codes during ideation and concept review activities

FREQUENCY VARIABLE	IDEATION						CONCEPT REVIEW					
	T1	T2	T3	T4	Mean	SD	T1	T2	T3	T4	Mean	SD
Problem analysis (n_{PA})	51	33	44	30	39.50	9.7	21	18	14	16	17.25	3.0
Problem synthesis (n_{PS})	74	47	41	34	49.00	17.5	9	10	14	10	10.75	2.2
Problem evaluation (n_{PE})	23	13	26	13	18.75	6.8	3	5	8	3	4.75	2.4
Solution analysis (n_{SA})	32	70	66	46	53.50	17.8	128	90	132	75	106.25	28.1
Solution synthesis (n_{SS})	72	97	105	99	93.25	14.6	72	71	89	64	74.00	10.6
Solution evaluation (n_{SE})	15	47	59	36	39.25	18.7	81	56	77	53	66.75	14.3
Process (n_{PROC})	25	14	24	16	19.75	5.6	16	18	15	13	15.50	2.1
Other (n_O)	22	24	18	14	19.50	4.4	13	20	26	11	17.50	6.9
Total of all coded segments	**314**	**345**	**383**	**288**	**332.50**	**40.9**	**343**	**288**	**375**	**245**	**312.75**	**57.7**
Analysis (n_A)	83	103	110	76	93.00	16.1	149	108	146	91	123.50	28.6
Synthesis (n_S)	146	144	146	133	142.25	6.2	81	81	103	74	84.75	12.6
Evaluation (n_E)	38	60	85	49	58.00	20.1	84	61	85	56	71.50	15.2
Problem-related (n_{PRO})	148	93	111	77	107.25	30.5	33	33	36	29	32.75	2.9
Solution-related (n_{SOL})	119	214	230	181	186.00	49.1	281	217	298	192	247.00	50.6
Total of ASE in problem and solution space (n)	**267**	**307**	**341**	**258**	**293.25**	**38.3**	**314**	**250**	**334**	**221**	**279.75**	**53.1**

T1 … T4 – Teams 1 to 4; Mean – average of all teams; SD – standard derivation of all teams

The segments related to the design space have been analysed individually (as ASE design operations in the problem and the solution space) but also aggregated into two categories: (1) ASE and (2) problem/solution-related (as proposed within the Chapter 3). The aggregated analysis design operation combines problem and solution analysis (n_{PA}+n_{SA}), the aggregated synthesis design operation combines problem and solution synthesis (n_{PS}+n_{SS}), and the aggregated evaluation design operation combines problem and solution evaluation (n_{PE}+n_{SE}). Similarly, aggregated problem space design operations combine problem analysis, synthesis and evaluation (n_{PA}+n_{PS}+n_{PE}), and the aggregated solution space design operations combine solution analysis, synthesis and evaluation (n_{SA}+n_{SS}+n_{SE}).

4.3.1. Observed proportions of design operations

For the purpose of focusing solely on ASE design operations within the problem and the solution space, the segments coded as other- and process-related discussion have been excluded from further analyses (frequency distribution and sequence analysis). Once the "process" and “other” segments were removed, the distribution of counted design operation segments (as presented in Table 4.3) was normalised in order to conduct further analyses using relative frequencies of design operations. Such normalisation implies that the sum of relative frequencies of all coded design operations segments equals 100%. The resulting distribution of relative frequencies of design operation segments for each of the four teams during the two conceptual design activities is shown in Figure 4.4.

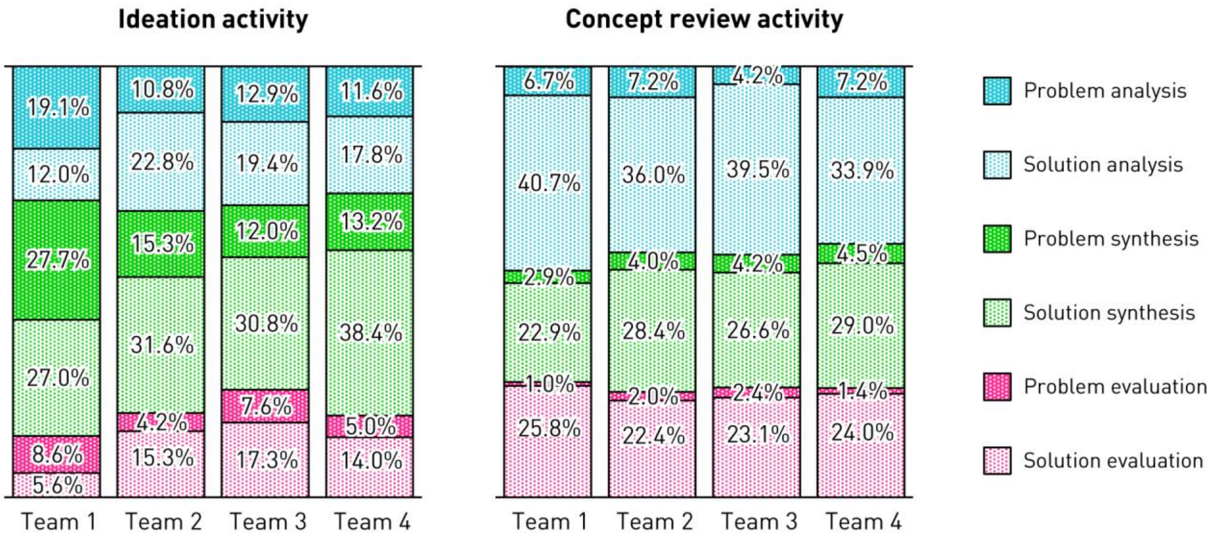

Figure 4.4 Proportions of design operation segments during ideation and concept review activities for all teams

From this point on, only the relative frequencies of design operations and sequences of design operations are used. For the sake of simplicity, relative frequencies will be referred to as proportions.

State-transition proportions during ideation activity

During the ideation activity, the most frequent ASE design operation in all four teams was synthesis (on average 49% of all ASE design operations per team), followed by analysis (32%), and evaluation (19%) as the least frequent. Of all design operations, on average 37% were performed in the problem space, and 63% in solution space. One of the teams (Team 1 in Figure 4.4) spent considerably more segments in the problem space (55%) than the other three (30-33%). On average, the most frequent design operation in problem space was problem synthesis (on average 46% of all design operations in problem space per team), followed by problem analysis (37%) and problem evaluation (17%). Similarly, the most frequent design operation in solution space was solution synthesis (on average 51% of all design operations in solution space per team), followed by solution analysis (28%) and solution evaluation (21%).

State-transition proportions during concept review activity

The descriptive statistics differ for the concept review activity, where the most frequent ASE design operation was analysis (on average 44% of all ASE design operations per team), followed by synthesis (31%) and evaluation (25%) as the least frequent. Of all design operations, on average 12% were performed in the problem space, and 88% in the solutions space, which is a considerable change compared to ideation. On average, the most frequent problem-space design operation was problem analysis (on average 53% of all design operations in problem space per team) followed by problem synthesis (33%) and problem evaluation (14%). The order concerning ASE is, again, the same in the solution space: solution analysis was the most frequent design operation in solution space (on average 43% of all design operations in solution space per team), followed by solution synthesis (30%) and solution evaluation (27%).

Differences in state-transition proportions between ideation and concept review activities

A triangular proportion visualisation was developed for qualitative comparison of ASE design operation proportions for each of the teams during the two activity types (Figure 4.5). The visualisation clearly shows that all four teams exhibit similar a direction considering the visualised proportion change. During ideation activity, all teams moderately gravitate towards the synthesis design operation. All teams align their process in the way that the shift in proportions can be visualised as moving towards analysis (right) and evaluation (bottom) within the triangular proportion visualisation.

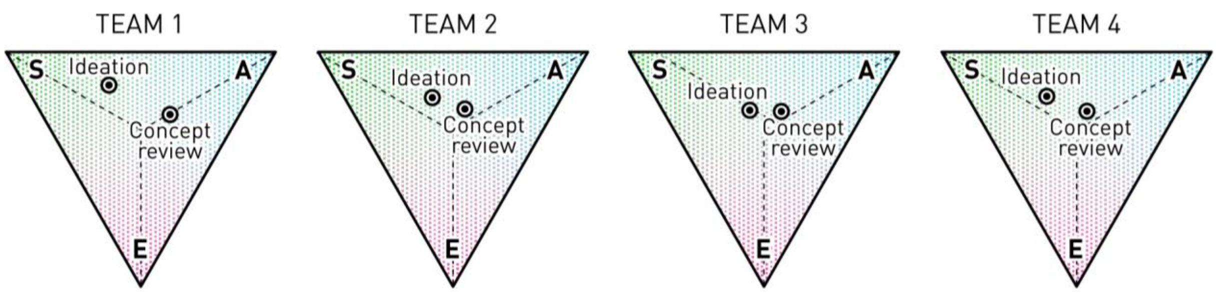

Figure 4.5 Visualisation of differences in ASE proportions between ideation and concept review activities for all teams

Additionally, a two-tailed paired-sample t-test was conducted to compare proportions of design operations separately and aggregated into both ASE and problem-solution space. Results of the test are given in Table 4.4. The normality of design operation distribution has been assumed following a similar approach by Mc Neill et al. [206]. Despite the small sample of teams, significant differences have been identified for the two conceptual design activities.

Table 4.4 T-test comparing proportions of design operations during ideation and concept review activities

PROPORTION VARIABLE	Ideation		Concept review		t value	P value
	Mean (%)	SD (%)	Mean (%)	SD (%)		
Problem analysis (p_{PA})	13.6	3.8	6.3	1.4	3.537	0.038*
Problem synthesis (p_{PS})	17.1	7.2	3.9	0.7	3.319	0.045*
Problem evaluation (p_{PE})	6.4	2.1	1.7	0.6	4.052	0.027*
Solution analysis (p_{SA})	18.0	4.5	37.6	3.1	-5.778	0.010*
Solution synthesis (p_{SS})	31.9	4.7	26.7	2.7	3.661	0.035*
Solution evaluation (p_{SE})	13.0	5.1	23.8	1.5	-3.297	0.046*
Analysis (p_{A})	31.6	1.7	43.9	2.6	-8.593	0.003**
Synthesis (p_{S})	49.0	5.2	30.6	3.4	4.932	0.016*
Evaluation (p_{E})	19.4	4.4	25.5	1.0	-2.442	0.092
Problem-related (p_{PRO})	37.0	12.3	11.9	1.5	3.751	0.033*
Solution-related (p_{SOL})	63.0	12.3	88.1	1.5	-3.751	0.033*

* $p<0.05$ ** $p<0.01$

There is a significant difference in proportions of ASE design operations in problem and solution space for ideation and concept review activities. Conducting one-tailed paired-sample t-test reveals that the proportions of problem analysis, problem synthesis, problem evaluation and solution synthesis are significantly higher ($p<0.05$) during the ideation activity. In contrast, the frequencies of solution analysis and solution evaluation are significantly higher ($p<0.05$) during the concept review activity.

Table 4.4 also shows a significant difference in proportions of design operations aggregated to ASE and problem-solution segments. Conducting one-tailed paired-sample t-test reveals that the proportion of analysis design operation is significantly higher ($p<0.01$) during the concept review activity, while the proportion of synthesis is significantly higher ($p<0.01$) during the ideation activity. Furthermore, the proportion of problem-related discussion is significantly higher ($p<0.05$) and the proportion of solution-related discussion is significantly lower ($p<0.05$) during the ideation activity, when compared to concept review activity.

4.3.2. Observed sequences of design operations

The probabilities of one design operation following another design operation, i.e. one state transition following another state transition have been interpreted as probability (Markov) matrices – square matrices used to describe the probabilities of moving from one element in the matrix (in this case a design operation) to all other elements [241]. It is here again noted that although a common term used to link the elements of a probability matrix is a “transition”, the term “move” is used to reduce the ambiguity when discussing transitions between design operations (transitions of transitions in the proposed model).

For each of the teams, the total number of moves between pairs of design operations have been counted and entered into the corresponding cells of the matrix. The rows of the matrix were normalised to calculate the probabilities (the sum of values in each row of a right stochastic matrix is 1). Each of the resulting matrices represents the probability matrix for that particular team. Probability matrices for all teams during ideation are reported in Table 4.5 and during concept review in Table 4.6.

Finally, in order to summarise the data, the probabilities matrices have been averaged per team. The resulting average probability matrices are shown in Table 4.7. Cells of the matrices have been coloured (heat map) to facilitate identification of moves between design operations that are most likely to appear.

During the ideation activity, the most probable design operation to come after problem analysis was problem synthesis (32.3% probability), after problem synthesis, it was problem analysis (28.9%), and after problem evaluation, it was also problem analysis (33.8%). Furthermore, solution analysis was most likely to be followed by solution synthesis (43.1%), solution synthesis by solution analysis (38.2%), and solution evaluation by solution synthesis (42.3%). As for the aggregated design operations, the most likely moves were as follows: analysis was most likely followed by synthesis (58.3%), synthesis by synthesis (40.5%) or analysis (40.0%), and evaluation by synthesis (54.9%).

During the concept review activity, the most likely moves starting with each of the ASE design operations in problem and solution space were as follows: problem analysis was most likely to be followed by solution synthesis (36.1%), problem synthesis by solution synthesis (34.8%), problem evaluation by solution analysis (46.5%), solution analysis by solutions synthesis (33.4%), solution synthesis by solution analysis (52.4%), and solution evaluation by solution analysis (44.7%). The most likely moves for each of the aggregated ASE design operations were as follows: analysis was most likely to be followed by synthesis (38.8%), synthesis by analysis (53.1%) and evaluation by analysis (53.4%). Please consult Table 4.7 for the probabilities of moves between all pairs of ASE design operations.

Table 4.5 Probability matrices for moves between ASE design operations in problem and solution space (left) and aggregated to ASE (right), obtained from ideation activity

ASE design operations in problem and solution space / **ASE design operations**

TEAM 1

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.137	0.529	0.176	0.000	0.157	0.000
PS→	0.356	0.329	0.178	0.000	0.137	0.000
PE→	0.391	0.304	0.043	0.000	0.261	0.000
SA→	0.094	0.281	0.000	0.094	0.406	0.125
SS→	0.056	0.083	0.000	0.319	0.389	0.153
SE→	0.067	0.067	0.000	0.400	0.467	0.000

	→A	→S	→E
A→	0.157	0.687	0.157
S→	0.366	0.469	0.166
E→	0.421	0.553	0.026

TEAM 2

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.152	0.333	0.152	0.030	0.333	0.000
PS→	0.149	0.319	0.106	0.064	0.255	0.106
PE→	0.308	0.231	0.077	0.077	0.231	0.077
SA→	0.057	0.129	0.014	0.157	0.386	0.257
SS→	0.093	0.062	0.010	0.423	0.258	0.155
SE→	0.065	0.065	0.000	0.283	0.413	0.174

	→A	→S	→E
A→	0.204	0.563	0.233
S→	0.417	0.403	0.181
E→	0.356	0.475	0.169

TEAM 3

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.182	0.227	0.273	0.023	0.182	0.114
PS→	0.268	0.171	0.244	0.024	0.268	0.024
PE→	0.269	0.308	0.038	0.038	0.346	0.000
SA→	0.077	0.046	0.015	0.077	0.431	0.354
SS→	0.057	0.057	0.019	0.429	0.267	0.171
SE→	0.119	0.119	0.000	0.220	0.339	0.203

	→A	→S	→E
A→	0.174	0.450	0.376
S→	0.432	0.356	0.212
E→	0.329	0.518	0.153

TEAM 4

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.067	0.200	0.167	0.000	0.533	0.033
PS→	0.382	0.206	0.235	0.000	0.176	0.000
PE→	0.385	0.308	0.000	0.077	0.231	0.000
SA→	0.087	0.065	0.000	0.109	0.500	0.239
SS→	0.031	0.061	0.000	0.357	0.337	0.214
SE→	0.083	0.222	0.000	0.139	0.472	0.083

	→A	→S	→E
A→	0.145	0.632	0.224
S→	0.386	0.394	0.220
E→	0.286	0.653	0.061

Table 4.6 Probability matrices for moves between ASE design operations in problem and solution space (left) and aggregated to ASE (right), obtained from concept review activity

ASE design operations in problem and solution space / **ASE design operations**

TEAM 1

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.143	0.095	0.000	0.238	0.429	0.095
PS→	0.000	0.000	0.222	0.222	0.333	0.222
PE→	0.000	0.000	0.000	0.667	0.000	0.333
SA→	0.063	0.016	0.008	0.242	0.320	0.352
SS→	0.028	0.000	0.000	0.611	0.042	0.319
SE→	0.100	0.063	0.000	0.538	0.200	0.100

	→A	→S	→E
A→	0.315	0.362	0.322
S→	0.593	0.074	0.333
E→	0.639	0.253	0.108

TEAM 2

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.000	0.059	0.118	0.294	0.294	0.235
PS→	0.400	0.000	0.300	0.100	0.100	0.100
PE→	0.400	0.000	0.000	0.400	0.000	0.200
SA→	0.044	0.044	0.000	0.289	0.356	0.267
SS→	0.056	0.014	0.000	0.423	0.324	0.183
SE→	0.071	0.071	0.000	0.446	0.179	0.232

	→A	→S	→E
A→	0.327	0.393	0.280
S→	0.481	0.309	0.210
E→	0.541	0.230	0.230

TEAM 3

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.143	0.071	0.143	0.214	0.286	0.143
PS→	0.214	0.000	0.143	0.071	0.357	0.214
PE→	0.375	0.000	0.000	0.125	0.375	0.125
SA→	0.023	0.038	0.008	0.288	0.379	0.265
SS→	0.011	0.022	0.000	0.539	0.101	0.326
SE→	0.013	0.079	0.039	0.539	0.237	0.092

	→A	→S	→E
A→	0.315	0.411	0.274
S→	0.515	0.155	0.330
E→	0.548	0.321	0.131

TEAM 4

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.000	0.000	0.063	0.500	0.438	0.000
PS→	0.200	0.000	0.100	0.100	0.600	0.000
PE→	0.000	0.000	0.000	0.667	0.000	0.333
SA→	0.053	0.093	0.000	0.227	0.280	0.347
SS→	0.048	0.000	0.000	0.524	0.111	0.317
SE→	0.132	0.057	0.019	0.264	0.434	0.094

	→A	→S	→E
A→	0.319	0.385	0.297
S→	0.534	0.178	0.288
E→	0.411	0.464	0.125

Table 4.7 Probability matrices for moves between ASE design operations in problem and solution space (left) and aggregated to ASE (right), obtained from ideation and concept review activities (both on average per team)

ASE design operations in problem and solution space / **ASE design operations**

Ideation activity

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.134	0.323	0.192	0.013	0.301	0.037
PS→	0.289	0.256	0.191	0.022	0.209	0.033
PE→	0.338	0.288	0.040	0.048	0.267	0.019
SA→	0.079	0.130	0.007	0.109	0.431	0.244
SS→	0.059	0.066	0.007	0.382	0.313	0.173
SE→	0.083	0.118	0.000	0.260	0.423	0.115

	→A	→S	→E
A→	0.170	0.583	0.247
S→	0.400	0.405	0.195
E→	0.348	0.549	0.102

Concept review activity

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.071	0.056	0.081	0.312	0.361	0.118
PS→	0.204	0.000	0.191	0.123	0.348	0.134
PE→	0.194	0.000	0.000	0.465	0.094	0.248
SA→	0.046	0.048	0.004	0.261	0.334	0.308
SS→	0.036	0.009	0.000	0.524	0.144	0.286
SE→	0.079	0.067	0.015	0.447	0.262	0.130

	→A	→S	→E
A→	0.319	0.388	0.293
S→	0.531	0.179	0.290
E→	0.534	0.317	0.148

Probability matrices of individual teams (Table 4.5 and Table 4.6) can be multiplied with the team's corresponding proportion of design operations segments (presented in Figure 4.4) to calculate proportions of particular moves between two design operations for that specific team. The obtained results correspond to the proportions of moves from one ASE design operation to another within the spaces (problem to problem and solution to solution) and in-between the spaces (problem to solution and solution to problem) in a single team. Proportion matrices of all four teams are shown in Table 4.8 for ideation, and in Table 4.9 for concept review activities.

Similar to the average probability matrices, the proportion-matrices can be averaged per teams in order to summarise the data. Averaged proportion matrices, which summarise the process of the ideation and concept review activities, are shown in Table 4.10.

Table 4.8 Proportions of moves between ASE design operations in problem and solution space (left) and aggregated to ASE (right), obtained from ideation activity

ASE design operations in problem and solution space / **ASE design operations**

TEAM 1

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.026	0.102	0.034	0.000	0.030	0.000
PS→	0.098	0.090	0.049	0.000	0.038	0.000
PE→	0.034	0.026	0.004	0.000	0.023	0.000
SA→	0.011	0.034	0.000	0.011	0.049	0.015
SS→	0.015	0.023	0.000	0.086	0.105	0.041
SE→	0.004	0.004	0.000	0.023	0.026	0.000

	→A	→S	→E
A→	0.049	0.214	0.049
S→	0.199	0.256	0.090
E→	0.060	0.079	0.004

TEAM 2

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.016	0.036	0.016	0.003	0.036	0.000
PS→	0.023	0.049	0.016	0.010	0.039	0.016
PE→	0.013	0.010	0.003	0.003	0.010	0.003
SA→	0.013	0.029	0.003	0.036	0.088	0.059
SS→	0.029	0.020	0.003	0.134	0.082	0.049
SE→	0.010	0.010	0.000	0.042	0.062	0.026

	→A	→S	→E
A→	0.069	0.190	0.078
S→	0.196	0.190	0.085
E→	0.069	0.092	0.033

TEAM 3

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.024	0.029	0.035	0.003	0.024	0.015
PS→	0.032	0.021	0.029	0.003	0.032	0.003
PE→	0.021	0.024	0.003	0.003	0.026	0.000
SA→	0.015	0.009	0.003	0.015	0.082	0.068
SS→	0.018	0.018	0.006	0.132	0.082	0.053
SE→	0.021	0.021	0.000	0.038	0.059	0.035

	→A	→S	→E
A→	0.056	0.144	0.121
S→	0.185	0.153	0.091
E→	0.082	0.129	0.038

TEAM 4

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.008	0.023	0.019	0.000	0.062	0.004
PS→	0.051	0.027	0.031	0.000	0.023	0.000
PE→	0.019	0.016	0.000	0.004	0.012	0.000
SA→	0.016	0.012	0.000	0.019	0.089	0.043
SS→	0.012	0.023	0.000	0.136	0.128	0.082
SE→	0.012	0.031	0.000	0.019	0.066	0.012

	→A	→S	→E
A→	0.043	0.187	0.066
S→	0.198	0.202	0.113
E→	0.054	0.125	0.012

Table 4.9 Proportions of moves between ASE design operations in problem and solution space (left) and aggregated to ASE (right), obtained from concept review activity

ASE design operations in problem and solution space | **ASE design operations**

TEAM 1

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.010	0.006	0.000	0.016	0.029	0.006
PS→	0.000	0.000	0.006	0.006	0.010	0.006
PE→	0.000	0.000	0.000	0.006	0.000	0.003
SA→	0.026	0.006	0.003	0.099	0.131	0.144
SS→	0.006	0.000	0.000	0.141	0.010	0.073
SE→	0.026	0.016	0.000	0.137	0.051	0.026

	→A	→S	→E
A→	0.150	0.173	0.153
S→	0.153	0.019	0.086
E→	0.169	0.067	0.029

TEAM 2

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.000	0.004	0.008	0.020	0.020	0.016
PS→	0.016	0.000	0.012	0.004	0.004	0.004
PE→	0.008	0.000	0.000	0.008	0.000	0.004
SA→	0.016	0.016	0.000	0.104	0.129	0.096
SS→	0.016	0.004	0.000	0.120	0.092	0.052
SE→	0.016	0.016	0.000	0.100	0.040	0.052

	→A	→S	→E
A→	0.141	0.169	0.120
S→	0.157	0.100	0.068
E→	0.133	0.056	0.056

TEAM 3

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.006	0.003	0.006	0.009	0.012	0.006
PS→	0.009	0.000	0.006	0.003	0.015	0.009
PE→	0.009	0.000	0.000	0.003	0.009	0.003
SA→	0.009	0.015	0.003	0.114	0.150	0.105
SS→	0.003	0.006	0.000	0.144	0.027	0.087
SE→	0.003	0.018	0.009	0.123	0.054	0.021

	→A	→S	→E
A→	0.138	0.180	0.120
S→	0.159	0.048	0.102
E→	0.138	0.081	0.033

TEAM 4

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.000	0.000	0.005	0.036	0.032	0.000
PS→	0.009	0.000	0.005	0.005	0.027	0.000
PE→	0.000	0.000	0.000	0.009	0.000	0.005
SA→	0.018	0.032	0.000	0.077	0.095	0.118
SS→	0.014	0.000	0.000	0.150	0.032	0.091
SE→	0.032	0.014	0.005	0.064	0.105	0.023

	→A	→S	→E
A→	0.132	0.159	0.123
S→	0.177	0.059	0.095
E→	0.105	0.118	0.032

Table 4.10 Averaged proportions of moves between ASE design operations in problem and solution space (left) and aggregated to ASE (right), obtained from ideation and concept review activities

ASE design operations in problem and solution space

Ideation activity

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.018	0.048	0.026	0.002	0.038	0.005
PS→	0.051	0.047	0.031	0.003	0.033	0.005
PE→	0.022	0.019	0.002	0.003	0.018	0.001
SA→	0.014	0.021	0.002	0.020	0.077	0.046
SS→	0.018	0.021	0.002	0.122	0.099	0.056
SE→	0.011	0.016	0.000	0.031	0.053	0.018

Concept review activity

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.004	0.003	0.005	0.020	0.023	0.007
PS→	0.009	0.000	0.007	0.004	0.014	0.005
PE→	0.004	0.000	0.000	0.007	0.002	0.004
SA→	0.017	0.017	0.002	0.099	0.126	0.116
SS→	0.010	0.003	0.000	0.139	0.040	0.076
SE→	0.019	0.016	0.003	0.106	0.062	0.030

ASE design operations

Ideation activity

	→A	→S	→E
A→	0.054	0.184	0.079
S→	0.195	0.200	0.095
E→	0.066	0.106	0.022

Concept review activity

	→A	→S	→E
A→	0.140	0.170	0.129
S→	0.162	0.057	0.088
E→	0.136	0.081	0.037

Moreover, the average proportion matrices have been mapped onto the two-dimensional state-transition model visualisation proposed in Figure 3.4, by adjusting the thickness of the transition arrows. The resulting visualisations (Figure 4.6 on team level for ideation; Figure 4.7 on team level for concept review; and Figure 4.8 on average for both activities) reflect the average proportional distribution of sequences of design operations throughout the ideation and the concept review activities.

Visualisations of state transitions have been developed to qualitatively compare the micro-scale design processes of teams engaged in ideation and concept review activities. Unlike the proportions of design operations presented in Table 4.4, the state-transition model visualisations provide additional insights on what design operations are likely to follow once a problem or solution entity has been analysed, synthesised or evaluated. Moreover, the overall thickness of the arrows entering the state nodes reflects the proportion of analysis, synthesis and evaluation during the activities.

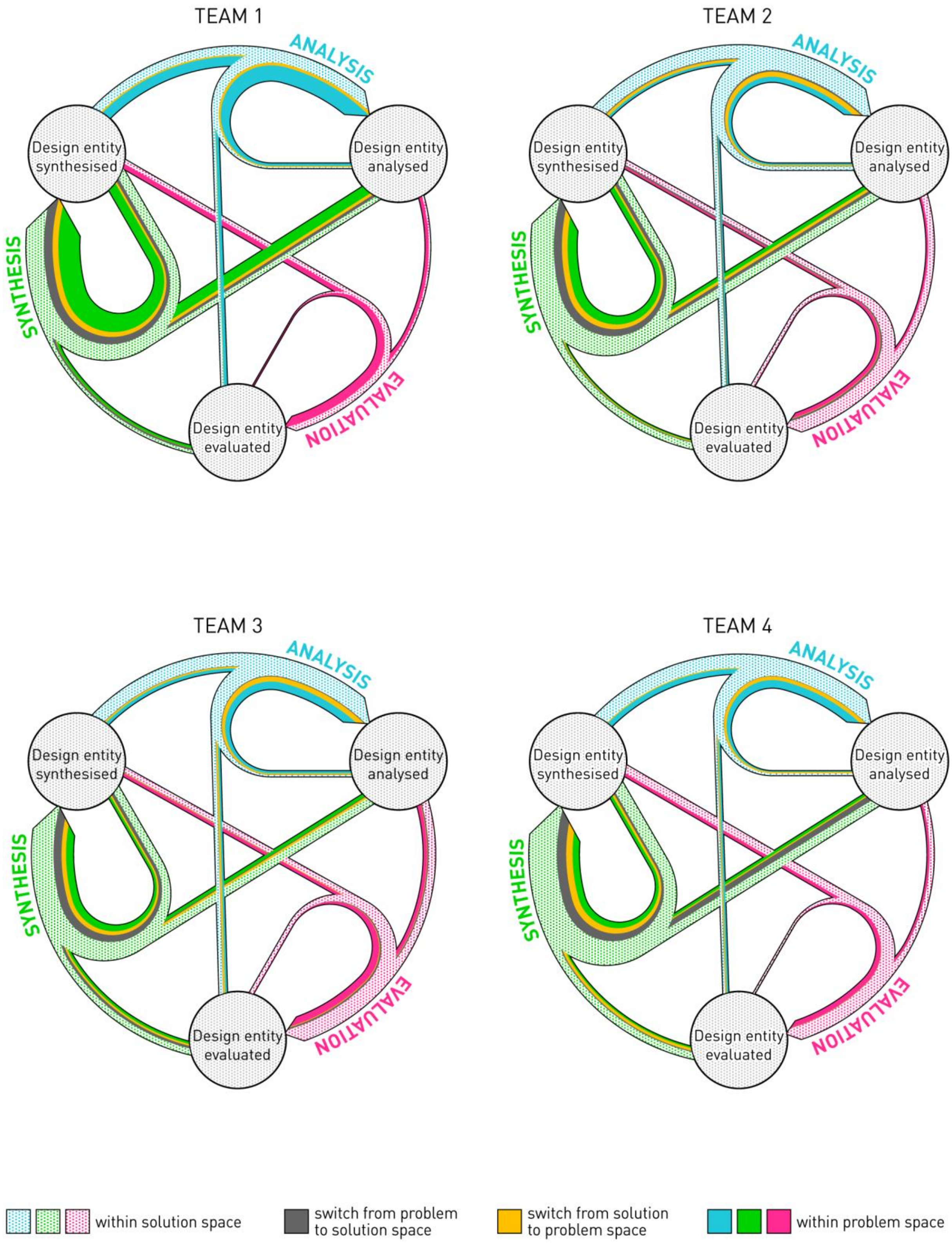

Figure 4.6 State-transition visualisation of proportions of sequences of ASE design operations within and in-between problem and the solution space for all teams during ideation activity

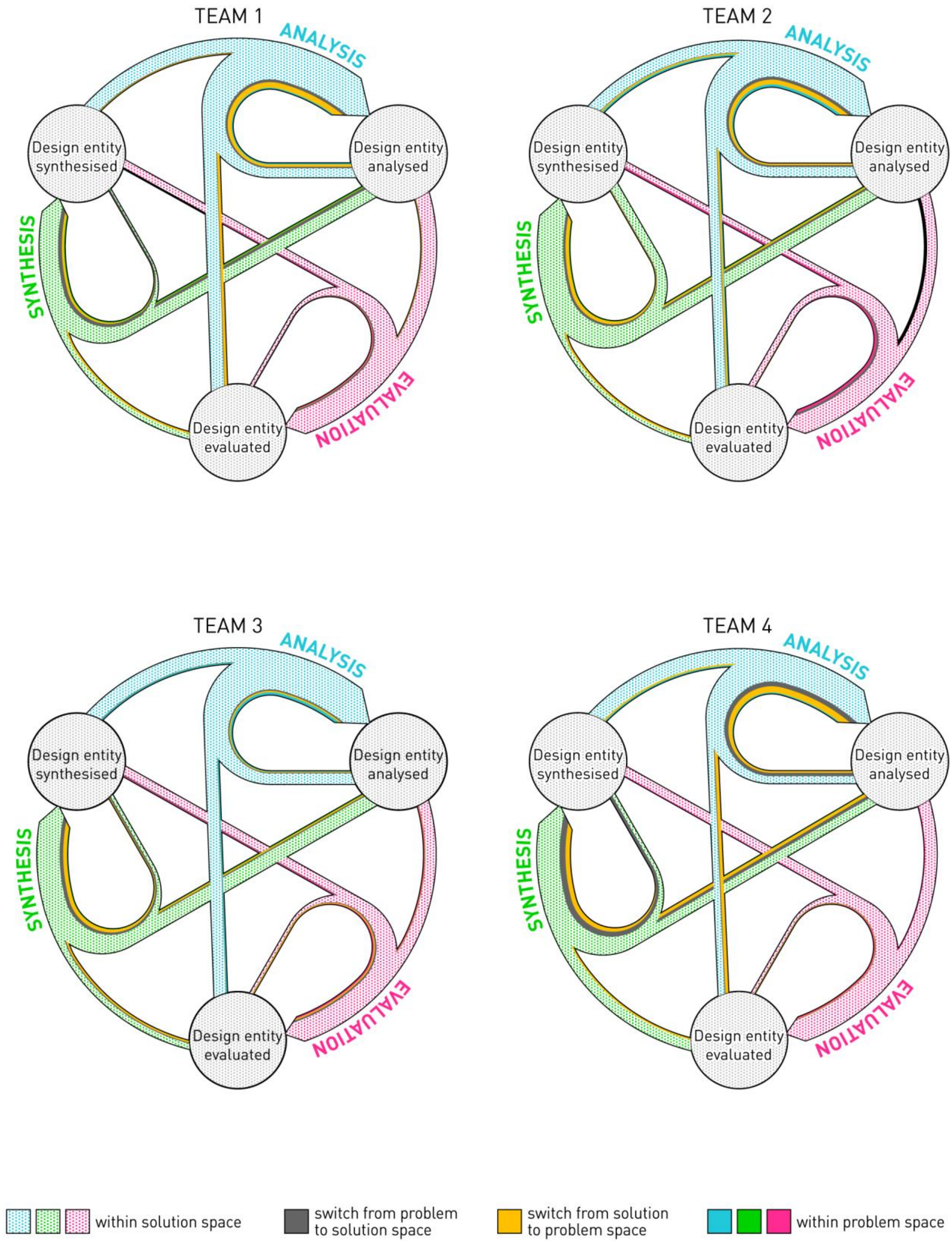

Figure 4.7 State-transition visualisation of proportions of sequences of ASE design operations within and in-between problem and the solution space for all teams during concept review activity

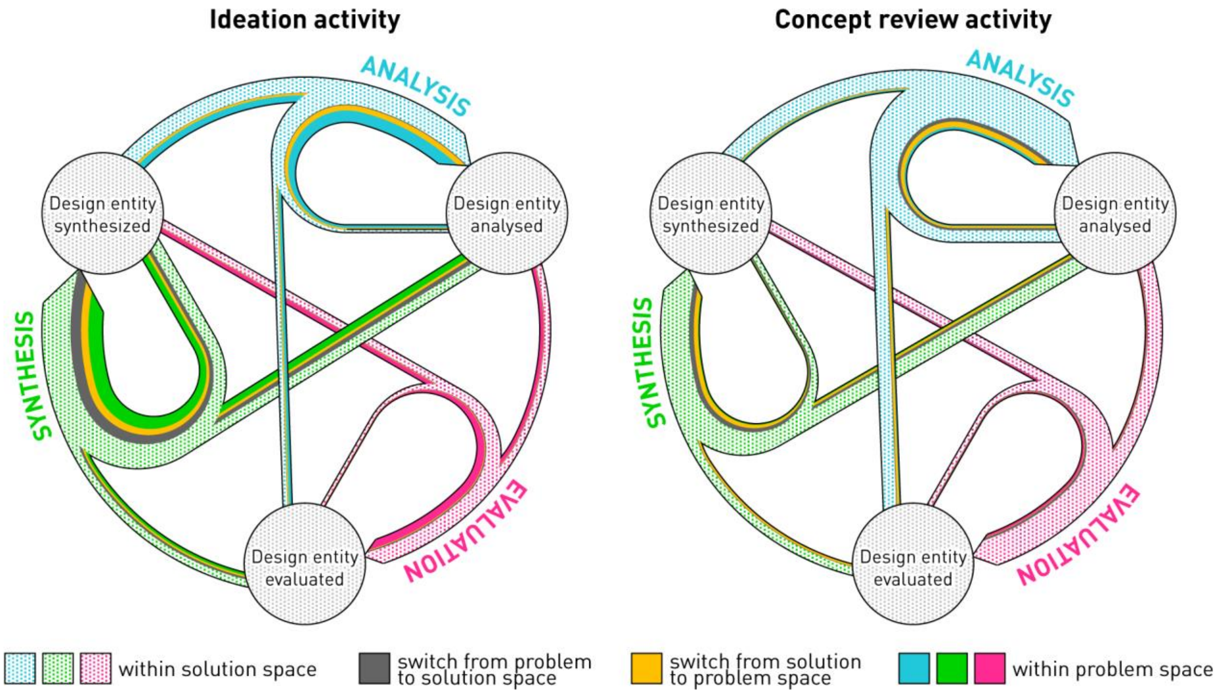

Figure 4.8 State-transition visualisation of average proportions of sequences of ASE design operations within and in-between problem and the solution space during ideation (left) and concept review (right) activity

The visualisations provide qualitative insights into:

- Traces of ASE performed within the problem space (continuous evolution of the problem space)
- Traces of ASE performed within the solution space (continuous evolution of the solution space)
- Traces of ASE performed to switch from problem to solution space, and from solution to problem space (co-evolution of the problem and the solution space)

In addition to the sequences of two design operations, the last part of sequence analysis includes the sequences of three consecutive design operations. Hence, instances of three design operations were counted and normalised for each of the teams, thus providing proportions of particular moves between three design operations. The resulting proportions were averaged across all teams (Table 4.11).

Sequences of multiple design operations should facilitate identification of patterns related to performing ASE design operations in the problem and the solution space. Nevertheless, mapping the proportions of sequences of three or more design operations onto the state-transition model results in visualisation identical to those shown in Figure 4.8.

Table 4.11 Averaged proportions of sequences of three consecutive design operations obtained from ideation and concept review activities

Ideation activity

	→PA	→PS	→PE	→SA	→SS	→SE
PA→PA→	0.004	0.007	0.003	0.000	0.003	0.002
PA→PS→	0.015	0.014	0.011	0.001	0.006	0.000
PA→PE→	0.008	0.009	0.000	0.001	0.008	0.001
PA→SA→	0.001	0.000	0.000	0.000	0.001	0.000
PA→SS→	0.002	0.000	0.000	0.012	0.016	0.009
PA→SE→	0.000	0.000	0.000	0.002	0.001	0.001
PS→PA→	0.006	0.023	0.009	0.000	0.013	0.001
PS→PS→	0.018	0.022	0.003	0.000	0.004	0.002
PS→PE→	0.011	0.008	0.003	0.002	0.009	0.000
PS→SA→	0.000	0.000	0.000	0.002	0.001	0.001
PS→SS→	0.002	0.003	0.000	0.012	0.009	0.008
PS→SE→	0.001	0.000	0.000	0.002	0.002	0.001
PE→PA→	0.003	0.006	0.006	0.000	0.006	0.000
PE→PS→	0.006	0.004	0.004	0.001	0.003	0.000
PE→PE→	0.001	0.001	0.000	0.000	0.001	0.000
PE→SA→	0.000	0.001	0.001	0.000	0.001	0.000
PE→SS→	0.002	0.001	0.000	0.010	0.005	0.001
PE→SE→	0.000	0.000	0.000	0.000	0.001	0.000
SA→PA→	0.001	0.005	0.005	0.000	0.003	0.000
SA→PS→	0.005	0.003	0.003	0.001	0.009	0.000
SA→PE→	0.001	0.001	0.000	0.000	0.000	0.000
SA→SA→	0.000	0.000	0.001	0.005	0.006	0.009
SA→SS→	0.003	0.007	0.000	0.028	0.027	0.012
SA→SE→	0.003	0.005	0.000	0.008	0.020	0.009
SS→PA→	0.003	0.003	0.002	0.001	0.010	0.001
SS→PS→	0.003	0.002	0.006	0.000	0.006	0.003
SS→PE→	0.001	0.001	0.000	0.000	0.001	0.000
SS→SA→	0.012	0.016	0.000	0.009	0.059	0.026
SS→SS→	0.004	0.007	0.001	0.041	0.027	0.018
SS→SE→	0.004	0.009	0.000	0.012	0.026	0.004
SE→PA→	0.002	0.002	0.002	0.001	0.004	0.001
SE→PS→	0.004	0.002	0.004	0.001	0.005	0.000
SE→PE→	0.000	0.000	0.000	0.000	0.000	0.000
SE→SA→	0.001	0.004	0.000	0.004	0.010	0.011
SE→SS→	0.007	0.002	0.001	0.019	0.016	0.009
SE→SE→	0.003	0.002	0.000	0.007	0.003	0.002

Concept review

	→PA	→PS	→PE	→SA	→SS	→SE
PA→PA→	0.000	0.001	0.001	0.002	0.000	0.000
PA→PS→	0.000	0.000	0.002	0.000	0.001	0.001
PA→PE→	0.002	0.000	0.000	0.000	0.002	0.001
PA→SA→	0.002	0.001	0.000	0.004	0.007	0.007
PA→SS→	0.002	0.000	0.000	0.010	0.006	0.005
PA→SE→	0.001	0.001	0.000	0.003	0.002	0.001
PS→PA→	0.001	0.000	0.001	0.003	0.004	0.000
PS→PS→	0.000	0.000	0.000	0.000	0.000	0.000
PS→PE→	0.002	0.000	0.000	0.005	0.000	0.001
PS→SA→	0.000	0.000	0.000	0.000	0.003	0.002
PS→SS→	0.001	0.001	0.000	0.007	0.000	0.005
PS→SE→	0.000	0.000	0.000	0.003	0.002	0.001
PE→PA→	0.000	0.001	0.001	0.000	0.002	0.001
PE→PS→	0.000	0.000	0.000	0.000	0.000	0.000
PE→PE→	0.000	0.000	0.000	0.000	0.000	0.000
PE→SA→	0.000	0.000	0.000	0.002	0.001	0.003
PE→SS→	0.000	0.000	0.000	0.002	0.000	0.001
PE→SE→	0.001	0.001	0.000	0.001	0.000	0.001
SA→PA→	0.002	0.002	0.000	0.006	0.005	0.003
SA→PS→	0.006	0.000	0.004	0.002	0.006	0.000
SA→PE→	0.001	0.000	0.000	0.000	0.000	0.001
SA→SA→	0.004	0.006	0.000	0.030	0.034	0.024
SA→SS→	0.001	0.001	0.000	0.068	0.018	0.039
SA→SE→	0.009	0.006	0.002	0.050	0.036	0.011
SS→PA→	0.000	0.000	0.000	0.003	0.004	0.003
SS→PS→	0.001	0.000	0.000	0.001	0.001	0.000
SS→PE→	0.000	0.000	0.000	0.000	0.000	0.000
SS→SA→	0.008	0.006	0.000	0.033	0.043	0.049
SS→SS→	0.001	0.001	0.000	0.020	0.010	0.009
SS→SE→	0.005	0.005	0.002	0.038	0.018	0.007
SE→PA→	0.001	0.000	0.002	0.006	0.009	0.000
SE→PS→	0.002	0.000	0.002	0.002	0.007	0.004
SE→PE→	0.000	0.000	0.000	0.002	0.001	0.001
SE→SA→	0.004	0.004	0.002	0.030	0.037	0.030
SE→SS→	0.005	0.000	0.000	0.034	0.007	0.017
SE→SE→	0.003	0.003	0.000	0.013	0.004	0.009

State-transition sequences during ideation activity

The averaged proportions of moves between ASE design operations during the ideation activity (Figure 4.8 on the left, based on Table 4.10) reveal several similarities in performing analysis, synthesis and evaluation within the problem and the solution space. For example, the most frequent sequences of two design operations within both spaces were synthesis to synthesis, synthesis to analysis and analysis to synthesis. The decreasing order of the remaining moves in both spaces was: synthesis to evaluation, analysis to evaluation, evaluation to analysis, analysis to analysis, and evaluation to evaluation. Nevertheless, the proportion of moves in problem and solution space differs largely in the case of the evaluation to synthesis sequence, which appeared primarily within the solution space.

Examination of three subsequent design operations (Table 4.11) reveals the most frequent sequences within the problem space: synthesis - analysis - synthesis (on average 2.3% of all sequences) and synthesis - synthesis - synthesis (2.2%); and within the solution space: synthesis - analysis - synthesis (5.9%) and synthesis - synthesis - analysis (4.1%).

Further insights can be derived from Table 4.10 and Figure 4.8. Regarding the moves from one space to another, teams would switch from solution to problem space mainly to perform problem synthesis (on average 5.8% of all moves per team), and problem analysis (4.3%). On average, the most frequent moves from solution to problem space were from solution analysis and solution synthesis to problem synthesis (both 2.1%), followed by moves from solution synthesis to problem analysis (1.8%) and solution evaluation to problem synthesis (1.6%). Only a few instances have been identified where teams switched the space to evaluate a problem (0.4% in total). As for the opposite direction, when switching to the solution space, teams did it primarily to synthesise solutions (on average 8.9% of all moves per team), and rather less frequently to evaluate (1.1%) or analyse (0.8%) solutions. Hence, problem analysis, synthesis and evaluation were all most likely to be followed by solution synthesis if space is switched.

Nevertheless, the probabilities of moves during the ideation activity (Table 4.7) show that once the teams switched from problem to solution space or vice versa, it was very likely that the next few transitions will remain in that space, before switching spaces again. Thus, the adding up of proportions of design operation moves presented in Table 4.10 shows that on average 52.4% of the moves took place within the solution space, 26.4% within the problem space, and 21.2% in-between the spaces. The most frequent sequence of three design operations which led to switching from problem to solution space was: problem synthesis - problem analysis - solution synthesis (on average 1.3% of all sequences). Similarly, the other way around it was: solution synthesis - solution analysis - problem synthesis (1.6%). Please consult Table 4.11 for a detailed proportional overview for sequences of three design operations.

State-transition sequences during concept review activity

The observed proportions of sequences of ASE design operations during concept review activity differ substantially in comparison to ideation (Figure 4.8 on the right, based on Table 4.10). For the most part, when the teams switched from solution to problem space during concept review, according to Table 4.7, it was unlikely that the next transitions would again be performed within the problem space. In contrast, when they switched from problem to solution space, it was likely for a larger number of solution-related design operations to follow. Thus, on average 79.5% of the design operation moves took place within the solution space and only 3.2% within the problem space, with 17.3% of moves in-between the problem and the solution space.

Consequently, as shown in Table 4.10 and Figure 4.8, the most frequent sequences of two design operations during concept review appeared solely within the solution space. These are, in decreasing order: synthesis to analysis (on average 13.9% of all moves per team), analysis to synthesis (12.6%), analysis to evaluation (11.6%), evaluation to analysis (10.6%) and analysis to analysis (9.9%). The most frequent sequences within the problem space were from synthesis to analysis (0.9%) and from synthesis to evaluation (0.7%). No moves from synthesis to synthesis, evaluation to synthesis and evaluation to evaluation have been identified within the problem space. Interestingly, such moves were also the least frequent within the solution space.

Further examination reveals that the most frequent sequences of three design operations (Table 4.11) within the solution space were analysis - synthesis - analysis (on average 6.8% of all sequences), analysis - evaluation - analysis (5.0%), and synthesis - analysis - evaluation (4.9%). As expected, due to the low proportion of problem-related moves, no frequent sequences of three design operations within the problem space can be singled out.

Teams most frequently switched from solution to problem space in order to analyse existing problems (on average 4.6% of all moves per team) or to synthesise new ones (3.6%). As shown in Table 4.10, these moves most often followed after solution evaluation and solution analysis. The other way around, teams frequently switched from problem space to solution space in order to perform solution synthesis (3.9%). For example, both problem analysis and problem synthesis were most frequently followed by solution synthesis once space was switched.

The most frequent sequences of three design operations which led to switching from problem to solution space were: problem synthesis - problem evaluation - solution analysis (0.5% of all sequences), and problem synthesis - problem analysis - solution synthesis (0.4%). The most frequent sequence from solution to problem space was solution analysis - solution evaluation - problem analysis (0.9%, see Table 4.11 for a detailed overview of sequences).

Differences in state-transition sequences between ideation and concept review activities

The significant differences in the probabilities of moves between design operations during ideation and concept review activities have been identified by performing a two-tailed paired-sample t-test on the probability matrices derived for each team (note that Table 4.7 shows only the mean values of probability matrices for all teams). Due to a relatively large number (36) of possible sequences of two design operations, only the sequences of significantly different probabilities are shown in Table 4.12.

Table 4.12 T-test comparing probabilities of design operation moves during ideation and concept review activities

Design operation sequence probability	Ideation		Concept review		t value	P value
	Mean	SD	Mean	SD		
Pr (PS | PA)	0.323	0.149	0.056	0.041	-3.438	0.022*
Pr (PE | PA)	0.192	0.055	0.081	0.063	-2.649	0.034*
Pr (SA | PA)	0.013	0.016	0.312	0.130	4.559	0.023*
Pr (PS | PS)	0.256	0.080	0.000	0.000	-6.426	0.008**
Pr (PS | PE)	0.288	0.038	0.000	0.000	-15.163	0.001**
Pr (SE | PE)	0.019	0.038	0.248	0.103	4.150	0.032*
Pr (PA | SA)	0.079	0.016	0.046	0.017	-2.824	0.030*
Pr (SA | SA)	0.109	0.035	0.261	0.032	6.487	0.005**
Pr (PS | SS)	0.066	0.012	0.009	0.011	-7.003	0.012*
Pr (SE | SS)	0.173	0.029	0.286	0.069	3.031	0.037*
Pr (SA | SE)	0.260	0.110	0.447	0.129	2.195	0.025*
Pr (A | A)	0.170	0.026	0.319	0.006	11.338	0.001*
Pr (S | A)	0.583	0.102	0.388	0.020	-3.747	0.049*
Pr (A | S)	0.400	0.030	0.531	0.047	4.728	0.038*
Pr (S | S)	0.405	0.047	0.179	0.097	-4.194	0.036*
Pr (E | S)	0.195	0.026	0.290	0.057	3.040	0.050
Pr (A | E)	0.348	0.057	0.534	0.094	3.404	0.003**
Pr (S | E)	0.549	0.076	0.317	0.106	-3.571	0.003**

* $p<0.05$ ** $p<0.01$

Out of 36 possible sequences of two design operations, 11 have been found to significantly differ in their probability during the ideation and the concept review activity (Table 4.12). One-tailed paired-sample t-test further reveals that the probabilities of design operation sequences directed towards the problem space (problem analysis to problem synthesis, problem analysis to problem evaluation, problem synthesis to problem synthesis, problem evaluation to problem synthesis, solution analysis to problem analysis and solution synthesis to problem synthesis) are significantly higher ($p<0.05$) during the ideation activity. Moreover, the probabilities of design operation sequences towards the solution space (problem analysis to solution analysis, problem evaluation to solution evaluation, solution analysis to solution analysis, solution synthesis to solution evaluation and solution evaluation to solution analysis) are significantly higher ($p<0.05$) during the concept review activity. As for the transitions aggregated into ASE, the probabilities of moves from analysis to synthesis, synthesis to synthesis and evaluation to synthesis are significantly higher ($p<0.05$) during the ideation activity, while the probabilities of moves from analysis to analysis, synthesis to analysis and synthesis to evaluation are significantly higher ($p<0.05$) during the concept review activity.

4.3.3. Moving average analysis of experiment sessions

Since the captured protocols are structured as time series data, it is possible to analyse also the change in proportions of design operations and sequences of design operations over the course of the observed design activity. Such analysis gives insight into foci on particular states and transitions with the activity progress. For this purpose, a moving average (windowing) approach (see, e.g. [206], [251], [252]) has been applied on coded protocols, as it provides a qualitative overview of the change in proportions of highly granular data. The moving average calculations create a series of averages protocol string subsets. The width of the sample window covers a fixed number of session protocol segments, which was set here at 15% of the total number of segments (based on experience, the 15% window offered the best ratio of the number of codes included in a window and the dynamics it has been able to exhibit). Hence, for each protocol segment, the average proportions of design operation codes and their sequences have been calculated by taking into consideration 15% of segments appearing before the analysed protocol segment. The window is moved from the start to the end of the session, one segment at a time.

The moving average analysis of the proportions of ASE design operations within the problem and the solution space during ideation and concept review activity has resulted in graphs shown in Figure 4.9. Hence, similarly to the graphs in Figure 4.4 showing the cumulative proportions of design operations during ideation and concept review, the graphs in Figure 4.9 show the change in these proportions over the course of the two activities.

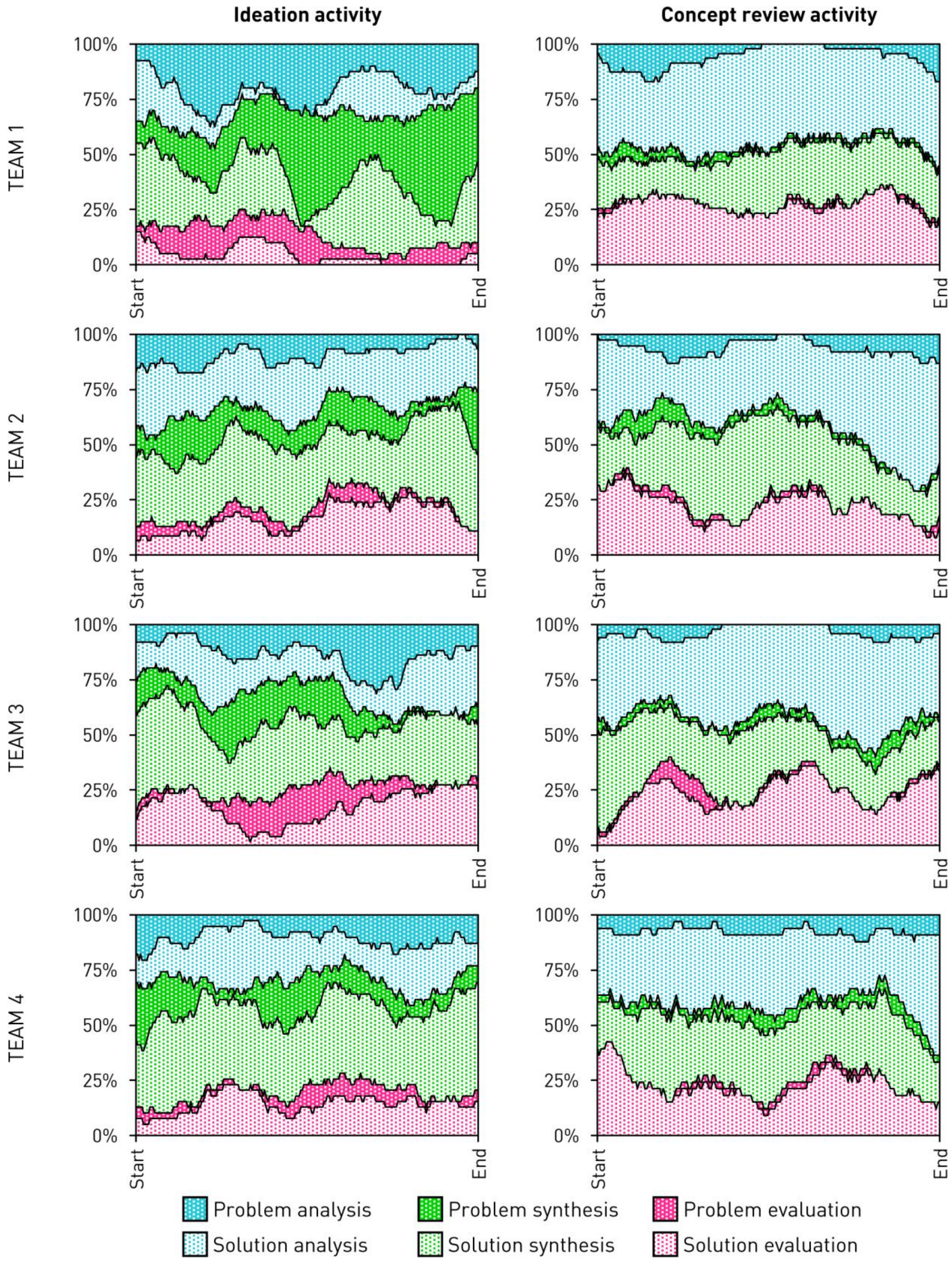

Figure 4.9 Overview of moving average proportions of ASE design operations within problem and solution space during ideation and concept review activities

The change of proportions of ASE design operations can also be represented within the triangular visualisations of ASE proportions (Figure 4.10). Again, analogous to the cumulative proportions of ASE design operations during ideation and concept review shown in Figure 4.5, these visualisations illustrate the change in ASE proportions throughout the two activities. Lapp [253] utilised a similar visualisation approach to show how agents explore two dimensions of the solution space.

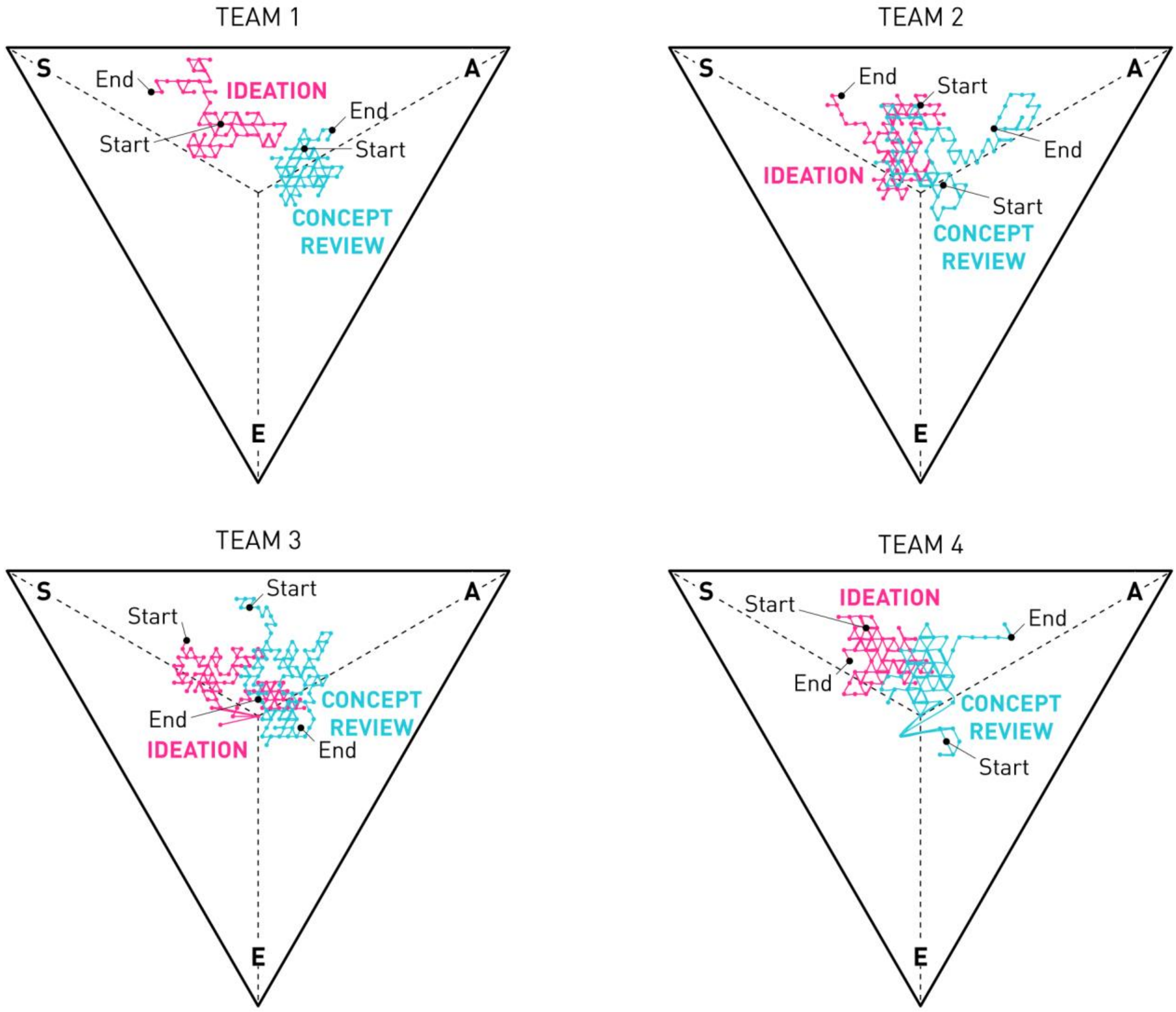

Figure 4.10 Triangular visualisation of moving average proportions of ASE design operations during idetion and concept review activities

Furthermore, moving average analysis can also be performed on proportions of sequences of two design operations. However, due to the relatively large number of moves between two ASE design operations within and in-between the problem and the solution space (36), only the aggregated moving average graphs are here presented. Hence, the changes in proportions of ASE sequences are shown in Figure 4.11, whereas the proportions of the sequences of problem- and solution-related design operations are shown in Figure 4.12.

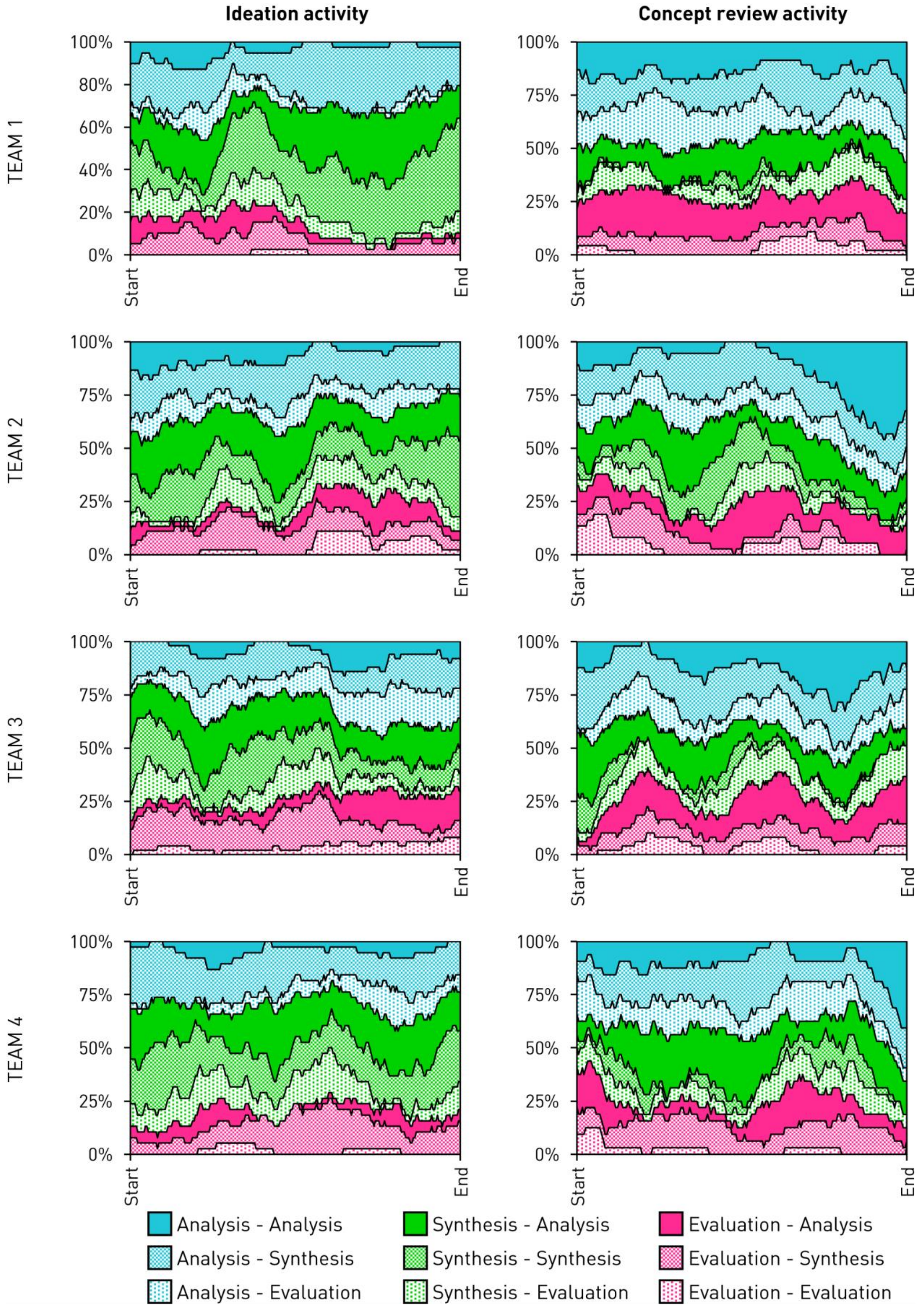

Figure 4.11 Overview of moving average proportions of sequences of ASE during ideation and concept review activities

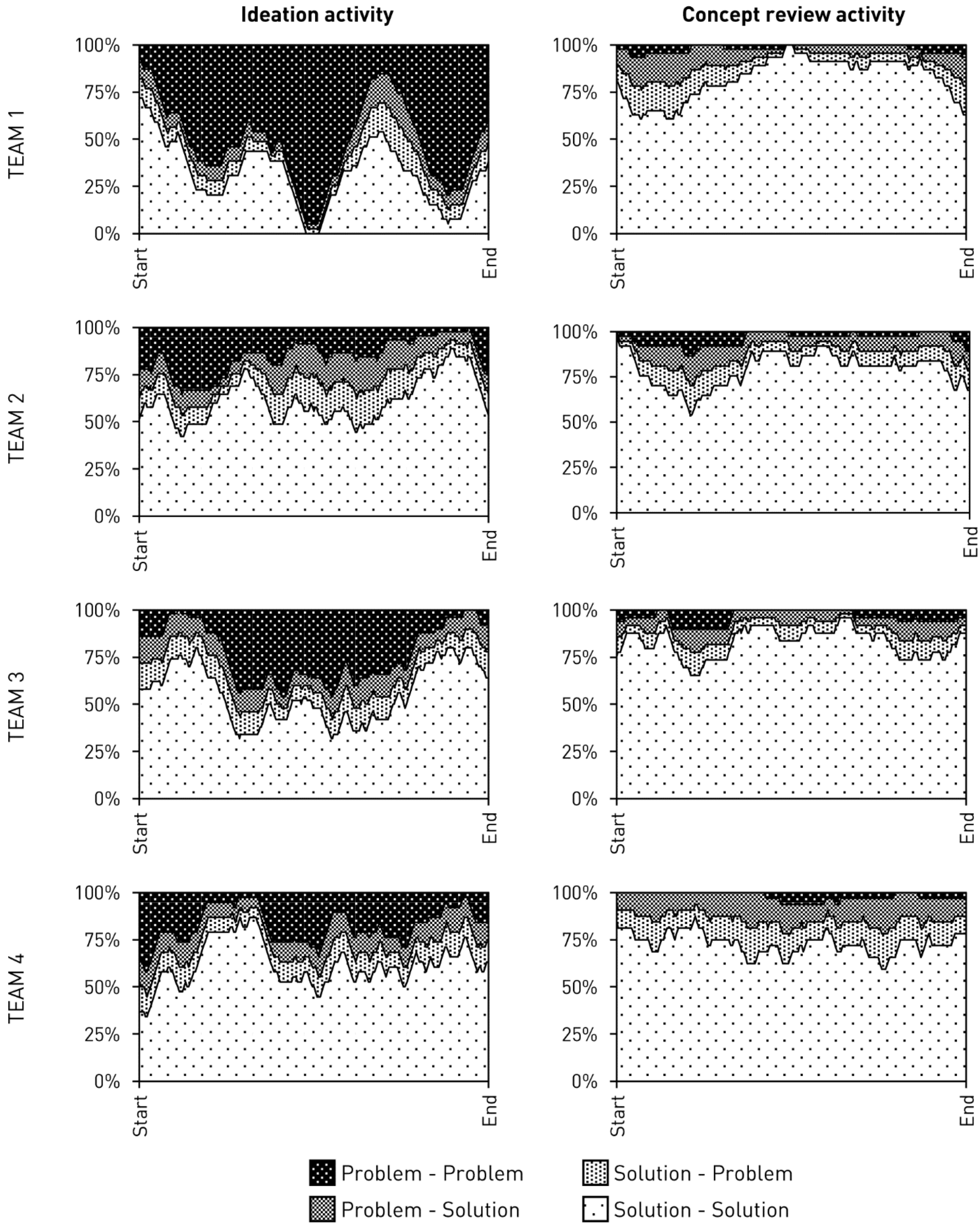

Figure 4.12 Overview of moving average proportions of sequences of problem- and solution-related design operation during ideation and concept review activities

The moving average graphs of proportions of design operations and of sequences of design operations enable qualitative analysis of designing in teams, particularly in terms of the dominant design operations at different stages of the observed design activity. The graphs reveal there exists an evident dynamic in the proportion change of different types of design operations as well as moves from one type of design operation to another. The latter applies for the way teams performed ASE as well as how they switched in-between the problem and the solution space. Although they have roughly explored similar parts of the triangular ASE proportion visualisation (Figure 4.10), the teams exhibited largely distinctive proportions of design operations and their sequences at different points of the process. The overall nature of the teams' processes in regard to these proportions is briefly described hereafter.

The process of Team 1 during ideation activity was the most problem-focused when compared to the other teams. The problem-focus is particularly evident in the form of three periods where problem analysis, synthesis and evaluation exhibit higher proportions (Figure 4.9). These periods are preceded and followed primarily by solution synthesis design operation, with relatively small proportions of solution analysis and evaluation. The process of Team 1 during concept review is significantly different, as shown in Figure 4.9. Problem-related design operations appear in small proportions at the beginning and the end of the session. Moreover, the changes in proportions of design operations are less evident when compared to ideation, as solution analysis and evaluation are dominant throughout the whole concept review activity.

In terms of ASE proportions, the ideation and concept review processes of Team 2 partially coincide, as shown in Figure 4.9. Similar proportions of ASE are particularly evident at the beginning of ideation and concept review activities. However, towards the end of ideation, the team progressed towards higher proportions of synthesis, whereas towards the end of concept review, the team progressed towards higher proportions of analysis. During both activities, the problem-related design operations are present mainly at the beginning of the session and decrease towards the end. Nevertheless, similarly to the other teams, the proportion of problem-related design operations is significantly higher throughout ideation when compared to concept review activity.

Team 3 started the ideation activity mainly by focusing on synthesising solutions, followed by evaluating solutions and synthesising problem, before finally analysing the problem and synthesising and analysing solutions. The focus on problem space in the middle of the ideation session is evident in Figure 4.12. A somewhat similar approach can be seen during the concept review, but with notably smaller proportions of problem-related design operations. Concept review thus starts primarily with the synthesis of solutions. Synthesis decreases towards the end of the activity, where solution analysis and evaluation prevail. Unlike during ideation, problem-related design operations are present at the beginning and the end of concept review.

Finally, the ideation process of Team 4 is characterised by problem synthesis and analysis at the beginning and in the middle of the session, and high proportions of solution synthesis throughout the rest of the session. On the other hand, with relatively low proportions of problem analysis and synthesis and negligible proportions of problem evaluation during concept review, the focus is primarily on solution development. Solution analysis and evaluation thus dominate the beginning and towards the end of concept review, whereas synthesis of solutions is relatively high throughout the middle of the session.

The data sets presented in Figures 4.9-4.12 together give a comprehensive and layered overview of the team design activity process, and a possible interplay between the proportions and sequences of design operations. For example, moving average analysis of the particular proportions and sequences of interest can be singled out and plotted onto the same graph, in order to qualitatively investigate the abovementioned interplay. Figure 4.13 shows an example of plotting graphs related to proportions of sequences of solution synthesis design operations during ideation activity of Team 1. The graphs include the change in the average proportion of synthesis, problem-related and solution synthesis design operations (dotted lines), and average proportions of sequences in-between synthesis and synthesis, solution and solution, and solution synthesis and solution synthesis design operations (solid lines).

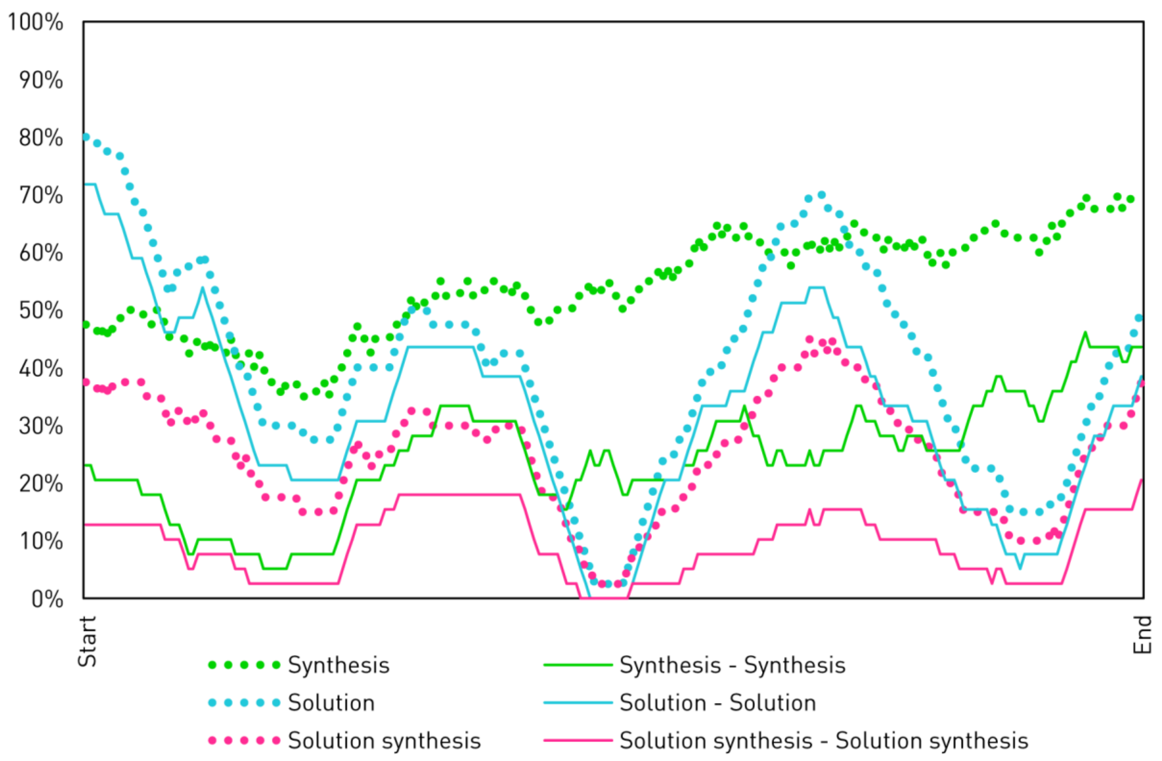

Figure 4.13 Moving average analysis of proportions related to sequences of solution synthesis design operation during ideation activity of Team 1

Another example concerning the sequence of solution synthesis to solution analysis design operation during the ideation activity of Team 2 is shown in Figure 4.14. The moving average analysis here includes proportions of analysis, solution-related and solution analysis design operations (dotted lines), as well as moves from synthesis to analysis, solution-related to solution-related and solution synthesis to solution analysis design operations (solid lines).

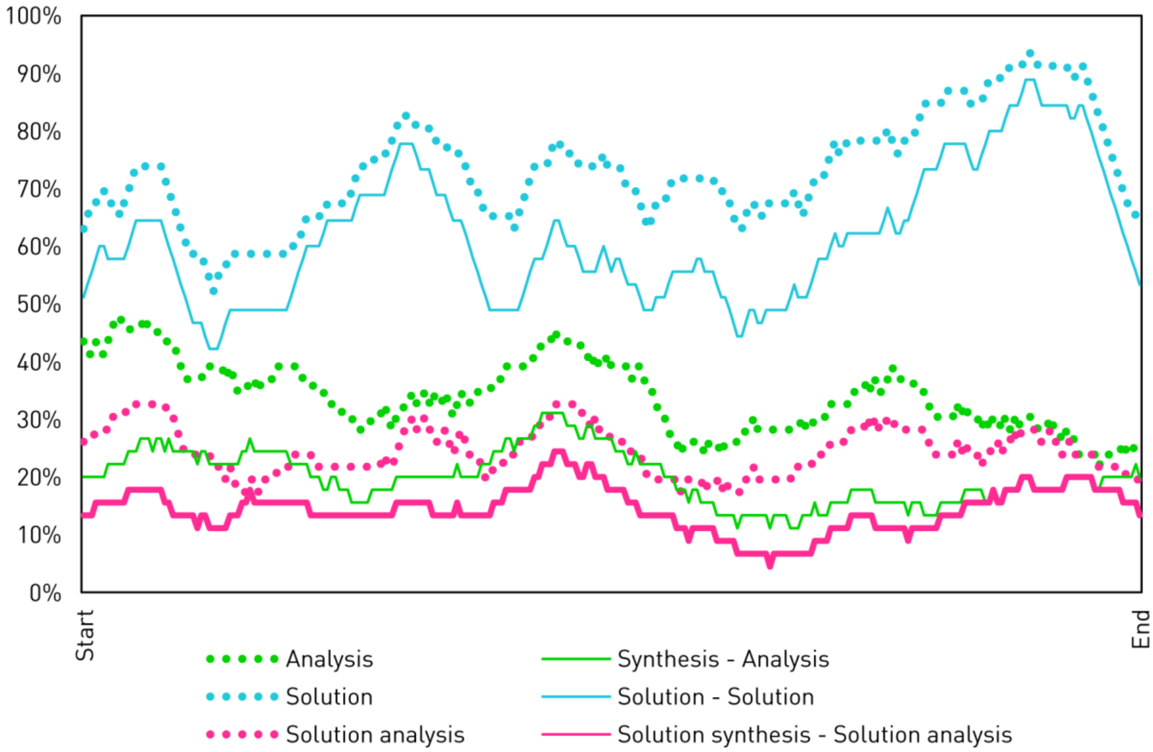

Figure 4.14 Moving average analysis of proportions related to moves from solution synthesis to solution analysis design operation during ideation activity of Team 2

Both examples exhibit a potential relationship between the proportions of ASE design operations within the problem and the solution space, and the proportions aggregated to ASE and problem- and solution-related design operations (pattern similarity across dotted lines), but also between the proportions of ASE design operation sequences within the problem and the solution space and the corresponding aggregation of sequences (pattern similarity across solid lines). Moreover, a qualitative similarity in patterns can also be discerned for the proportions of design operations and the proportions of their sequences (pattern similarity across line colours).

The nature of these relationships and the utility of using the relationships to model other scenarios of team conceptual design activity is further explored within the next chapter. The analysis results from the here presented protocol analysis study provide a sufficient dataset for the exploratory analysis and modelling of the hypothesised interplay between proportions and sequences of design operations. The proportions of design operations and their sequences introduced as part of the theoretical model in Chapter 3 are formalised within the mathematical model using the experimental data. The mathematical model can be utilised as a means of simulating proportions and sequences of design operations for different setups of team conceptual design activity, as demonstrated in Chapter 6.

5. MATHEMATICAL MODEL

The fifth chapter builds on the results of the protocol analysis study, primarily by means of statistical and stochastic modelling of relationships identified within the obtained protocol data. The relationships between proportions of design operations and proportions and probabilities of their sequences have been formalised using regression analysis. The resulting regression equations have then been synthesised in the form of a mathematical model of state transitions during team conceptual design activity. Finally, the mathematical model has been tested by replicating the results of the protocol analysis study.

The previous chapter presents the results of utilising the theoretical framework as a means of gathering, structuring and analysing data related to the process of team conceptual design activity. This chapter further investigates the potential relationships within the interpreted data, and utilises the new insights for further prescriptive development, particularly in terms of modelling the proportions and probabilities of sequences of design operations for different setups of team conceptual design activity. In the context of this dissertation, the ability to model different scenarios of team conceptual design activity is essential for addressing research questions RQ4 and RQ5, that is how the identified patterns of ASE design operations are likely to change with the progress of the conceptual design stage and what are the prevalent patterns of ASE design operations in different types of engineering design projects (e.g. innovative and adaptive design).

The regression analysis has been used to quantify the relationships [254] in-between the state-transition variables introduced within Chapter 3. More precisely, a linear and polynomial regression analysis approaches were run to investigate the relationships between proportions and sequences of design operations. Simple regression involves only two variables – a predictor (independent) variable and a response (dependent) variable. Multiple regression is an obvious generalisation of simple linear regression, as it allows multiple predictor variables instead of one predictor variable [254]. Generally, when applying linear regression, the observed data is used to fit a model of the relationship between a scalar dependent variable and one or more explanatory (independent) variables [255]. Polynomial regression is (from here on) considered a special case of multiple linear regression. The regression approach is simple to apply but assumes that the design variables in the regression are linear and that the effect of an independent design variable is constant throughout the entire range of the response [256].

Given the theoretical framework described within Chapter 3, a total of three fundamental independent variables have been identified: two variables which define the vector within the ASE proportion triangle (distance from the triangle centre r and angle δ), which corresponds to the proportions of analysis, synthesis and evaluation (Equations 3.5-3.7), and one variable which defines the proportions of design operations within the problem and the solution space. These three independent variables thus represent the input parameters needed for calculating (predicting) the dependent variables, that is the proportions and probabilities of sequences of ASE design operation within and in-between the problem and the solution space (e.g. using computational simulation tools). For the sake of simplicity, the vector variables and the problem/solution ratio have not been directly used. Instead, the regression has been performed using the proportions of analysis, synthesis and evaluation ($p_A + p_S + p_E = 1$), and the proportions of problem- and solution-related design operations ($p_{PRO} + p_{SOL} = 1$).

Linear regression modelling was conducted using the R software [254], [257]. Since the effects of intercepts are not significant, they have been excluded from the linear regression analysis. In this way, only one coefficient is sufficient to describe a particular relationship. Moreover, the regression models include only interactions terms or squared terms (without including the main effects). There are two reasons for this. First, the main effects have in general not been found significant. Second, the modelling purpose is solely to predict proportions of design operations and their sequences, rather than statistical inference about each of the effects. The normality of the error distribution in the regression models was tested using the Shapiro-Wilk test [254]. These results are also reported hereafter. Other linear regression diagnostics have been performed as part of the modelling process by plotting diagnostic plots (observed versus predicted values, residuals versus predicted values).

The results of linear regression modelling are reported in two parts. In Section 5.1, the proportions of design operations p_{PA}, p_{PS}, p_{PE}, p_{SA}, p_{SS} and p_{SE} are formulated as functions of ASE proportions and the proportions of the problem- and solution-related design operations. In Section 5.2, the proportions of sequences of two design operations (e.g. $p_{PA,PA}$, $p_{PA,PS}$,…) are formulated as functions of design operation proportions (both aggregated – e.g. $p_{A,A}$, $p_{A,S}$, $p_{PRO,PRO}$, etc. – and unaggregated – e.g. $p_{PA,PA}$, $p_{PA,PS}$, etc.). Finally, in Section 5.3, all formulated regression equations are integrated as part of a single mathematical model, and the model is used to generate data related to design operation proportions and sequences, with input variables being the data from the protocol analysis study. A qualitative comparison of the observed and simulated data is then performed to initially validate the predictive ability of the mathematical model.

5.1. Modelling proportions of design operations

Several iterations of linear regression modelling have been conducted on the design operation proportions data gathered from the protocol analysis study (Chapter 4). The best fit has been reached for the following hypothesised relationship: *The proportion of either one of ASE design operations within the problem or the solution space is proportional to the product of the corresponding proportions of ASE and problem/solution-related design operations.*

Symbolically, the formulated relationship can be written as shown in Equation 5.1.

$$p_{xy} = k_{xy} \cdot p_x \cdot p_y \,, \qquad x = \{PRO;SOL\}, \quad y = \{A;S;E\} \qquad \text{(Equation 5.1)}$$

The initial number of data points for linear regression was relatively small – one point per observed experiment session (8 data points in total), which corresponds to the average proportions of design operations during the whole activity (reported throughout the Subsection 4.3.1). In order to increase the number of data points, the protocol strings, which consist of 221-341 design operations codes, have been split into two (16 data points) and three (24 data points) equal subsets of protocol strings. The rationale for splitting the protocol strings lies in the assumption that the hypothesised relationships should be consistent not only on the activity level but also at different fragments of the activity. The fitting results of the regression analysis using 8, 16 and 24 points (based on one, two and three fragments of the observed experiment sessions) are shown in Figure 5.1.

The results confirm the assumption that the relationship between proportions is consistent no matter which fragment of activity is observed – namely, the differences between the three cases of linear regression range from 0.1% to 5.2%. Furthermore, the higher the number of instances of a particular design operation (n_i) in a protocol string, the more insignificant difference exists between the three cases of linear regression. For example, solution analysis, synthesis and evaluation design operations, which were the most frequent instances on average, exhibit only 0.1%, 0.2% and 0.2% difference respectively, whereas problem evaluation as the least frequent instance manifests 5.2% difference. Hence, increasing the number of data points by splitting the initial protocol strings into smaller fragments can be performed as long as a sufficient number of instances of each design operations is present within the protocol string fragments.

For this reason, the splitting of protocol strings into less than three fragments has not been performed. The relationships described hereafter result from analysis using 24 data points.

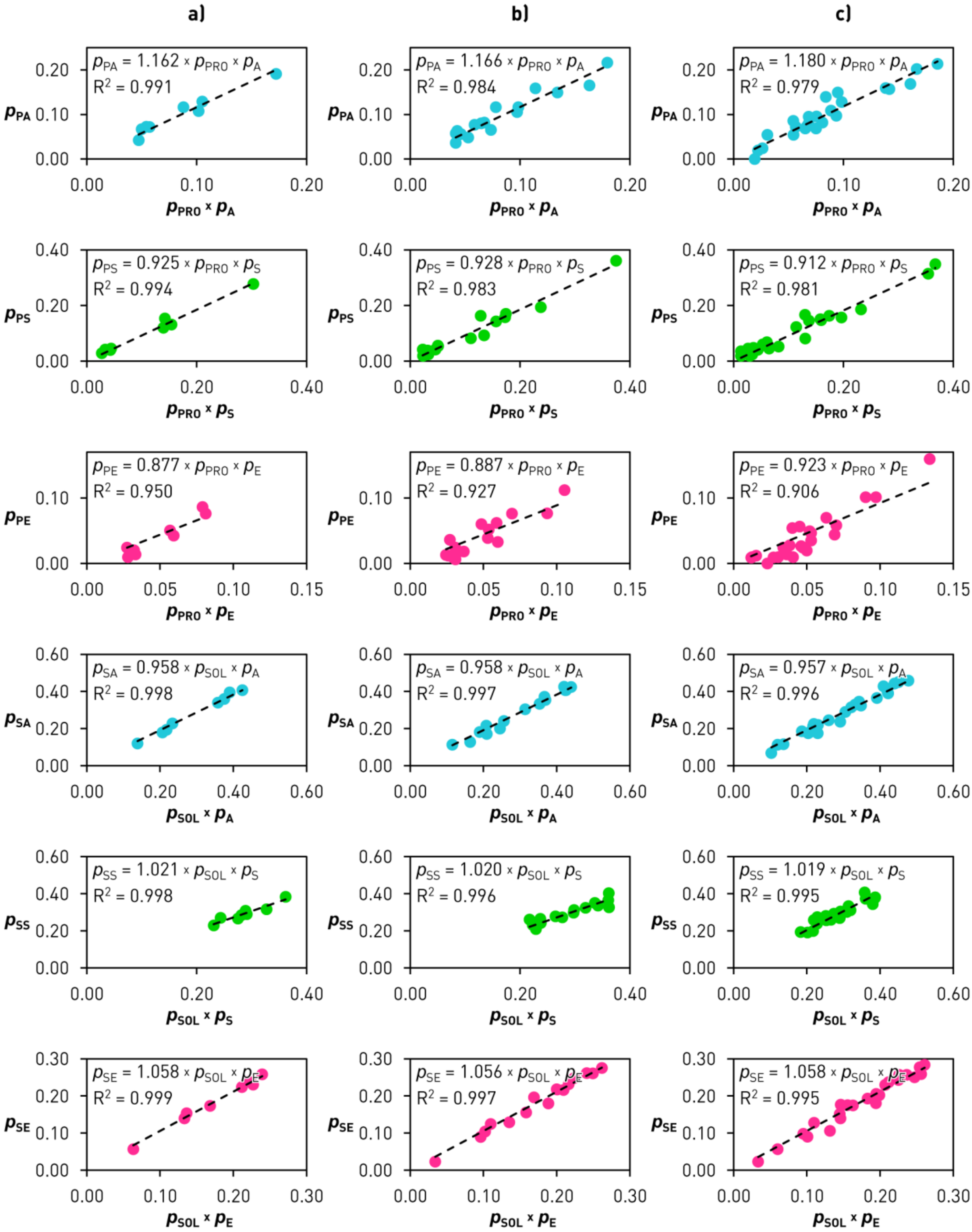

Figure 5.1 Relations between unaggregated design operations as dependent variables and design operations aggregated into ASE and problem/solution as independent variables: a) total activities; b) activities split into two parts; c) activities split into three parts

Proportion of problem analysis – A multiple linear regression was calculated to predict the proportion of problem analysis based on the interaction of proportions of analysis and problem-related design operations. A significant regression equation (Equation 5.2) was found ($F(1,23)=1076$, $p<0.000$) with an $R^2=0.979$. The interaction significantly predicted the proportion of problem analysis ($\beta=0.989$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.928$, $p=0.088$).

$$p_{PA} = 1.180 \cdot p_A \cdot p_{PRO} \qquad \text{(Equation 5.2)}$$

Proportion of problem synthesis – A multiple linear regression was calculated to predict the proportion of problem synthesis based on the interaction of proportions of synthesis and problem-related design operations. A significant regression equation (Equation 5.3) was found ($F(1,23)=1195$, $p<0.000$) with an $R^2=0.981$. The interaction significantly predicted the proportion of problem synthesis ($\beta=0.991$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.974$, $p=0.772$).

$$p_{PS} = 0.912 \cdot p_S \cdot p_{PRO} \qquad \text{(Equation 5.3)}$$

Proportion of problem evaluation – A multiple linear regression was calculated to predict the proportion of problem evaluation based on the interaction of proportions of evaluation and problem-related design operations. A significant regression equation (Equation 5.4) was found ($F(1,23)=222.8$, $p<0.000$) with an $R^2=0.906$. The interaction significantly predicted the proportion of problem evaluation ($\beta=0.952$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.938$, $p=0.150$).

$$p_{PE} = 0.923 \cdot p_E \cdot p_{PRO} \qquad \text{(Equation 5.4)}$$

Proportion of solution analysis – A multiple linear regression was calculated to predict the proportion of solution analysis based on the interaction of proportions of analysis and solution-related design operations. A significant regression equation (Equation 5.5) was found ($F(1,23)=5388$, $p<0.000$) with an $R^2=0.996$. The interaction significantly predicted the proportion of solution analysis ($\beta=0.998$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.977$, $p=0.845$).

$$p_{SA} = 0.957 \cdot p_A \cdot p_{SOL} \qquad \text{(Equation 5.5)}$$

Proportion of solution synthesis – A multiple linear regression was calculated to predict the proportion of solution synthesis based on the interaction of proportions of synthesis and solution-related design operations. A significant regression equation (Equation 5.6) was found

($F(1,23)=4217$, $p<0.000$) with an $R^2=0.995$. The interaction significantly predicted the proportion of solution synthesis ($\beta=0.997$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.957$, $p=0.372$).

$$p_{SS} = 1.019 \cdot p_S \cdot p_{SOL} \qquad \text{(Equation 5.6)}$$

Proportion of solution evaluation – A multiple linear regression was calculated to predict the proportion of solution evaluation based on the interaction of proportions of evaluation and solution-related design operations. A significant regression equation (Equation 5.7) was found ($F(1,23)=4854$, $p<0.000$) with an $R^2=0.995$.

$$p_{SE} = 1.058 \cdot p_E \cdot p_{SOL} \qquad \text{(Equation 5.7)}$$

The above-listed equations enable modelling of proportions of six ASE design operations in problem and solution space based on three independent variables. The response provided by the equations can be used to perform moving average analysis of design operations proportions as shown in Figure 4.9 and gain qualitative insights into trends of performing design operations throughout different configurations of team conceptual design activity. The ability of the formulated linear regression models to reflect design operation proportions captured in the protocol analysis study is investigated in Section 5.2.

5.2. Modelling sequences of design operations

The modelling of proportions of sequences of design operations has been conducted in a similar manner as modelling proportions of design operations. The relationship hypothesis investigated through several iterations of simple and multiple linear regression modelling was that the proportions of moves between two design operations are proportional to the product of proportions of these two design operations.

5.2.1. Sequences of ASE design operations

The modelling was first conducted for the proportions of moves between analysis, synthesis and evaluation (design operations aggregated into ASE). After iterative regression modelling, the following relationship has been hypothesised: *The proportion of moves between two ASE design operations is proportional to the product of the corresponding proportions of ASE design operations.* Symbolically, this relationship can be written as shown in Equation 5.8.

$$p_{x,y} = k_{x,y} \cdot p_x \cdot p_y \,, \qquad x, y = \{A;S;E\} \qquad \text{(Equation 5.8)}$$

As shown in Figure 5.2, linear regression has again been performed for three cases: the complete protocol strings (8 data points), protocol strings split into two fragments (16 data points), and protocol strings split into three fragments (24 data points). The results confirm the assumption that the relationship between proportions is consistent no matter which fragment of activity is observed since the differences in-between the three cases of linear regression range from 0.7% to 4.2%. Again, the highest difference was found for the sequence with the lowest number of instances within the fragments (evaluation to evaluation).

Proportion of analysis to analysis sequences – A simple linear regression was calculated to predict the proportion of moves from analysis to analysis based on the squared proportion of analysis design operation. A significant regression equation (Equation 5.9) was found (F(1,23)=287.8, p<0.000) with an R^2=0.926. The squared proportion significantly predicted the proportion of analysis to analysis sequences (β=0.962, p<0.000). However, the Shapiro-Wilk test rejected the normality assumption at the significance level of 0.05 (W=0.876, p=0.007). The issue of non-normal error distribution is addressed in Section 5.3.

$$p_{\mathrm{A,A}} = 0.703 \cdot p_{\mathrm{A}}^2 \qquad \text{(Equation 5.9)}$$

Proportion of analysis to synthesis sequences – A multiple linear regression was calculated to predict the proportion of moves from analysis to synthesis based on the interaction of proportions of analysis and proportion of synthesis design operations. A significant regression equation (Equation 5.10) was found (F(1,23)=1452, p<0.000) with an R^2=0.984. The interaction significantly predicted the proportion of analysis to synthesis sequences (β=0.992, p<0.000). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 (W=0.943, p=0.194).

$$p_{\mathrm{A,S}} = 1.253 \cdot p_{\mathrm{A}} \cdot p_{\mathrm{S}} \qquad \text{(Equation 5.10)}$$

Proportion of analysis to evaluation sequences – A multiple linear regression was calculated to predict the proportion of moves from analysis to evaluation based on the interaction of proportions of analysis and proportion of evaluation design operations. A significant regression equation (Equation 5.11) was found (F(1,23)=691.3, p<0.000) with an R^2=0.968. The interaction significantly predicted the proportion of analysis to evaluation sequences (β=0.984, p<0.000). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 (W=0.981, p=0.917).

$$p_{\mathrm{A,E}} = 1.194 \cdot p_{\mathrm{A}} \cdot p_{\mathrm{E}} \qquad \text{(Equation 5.11)}$$

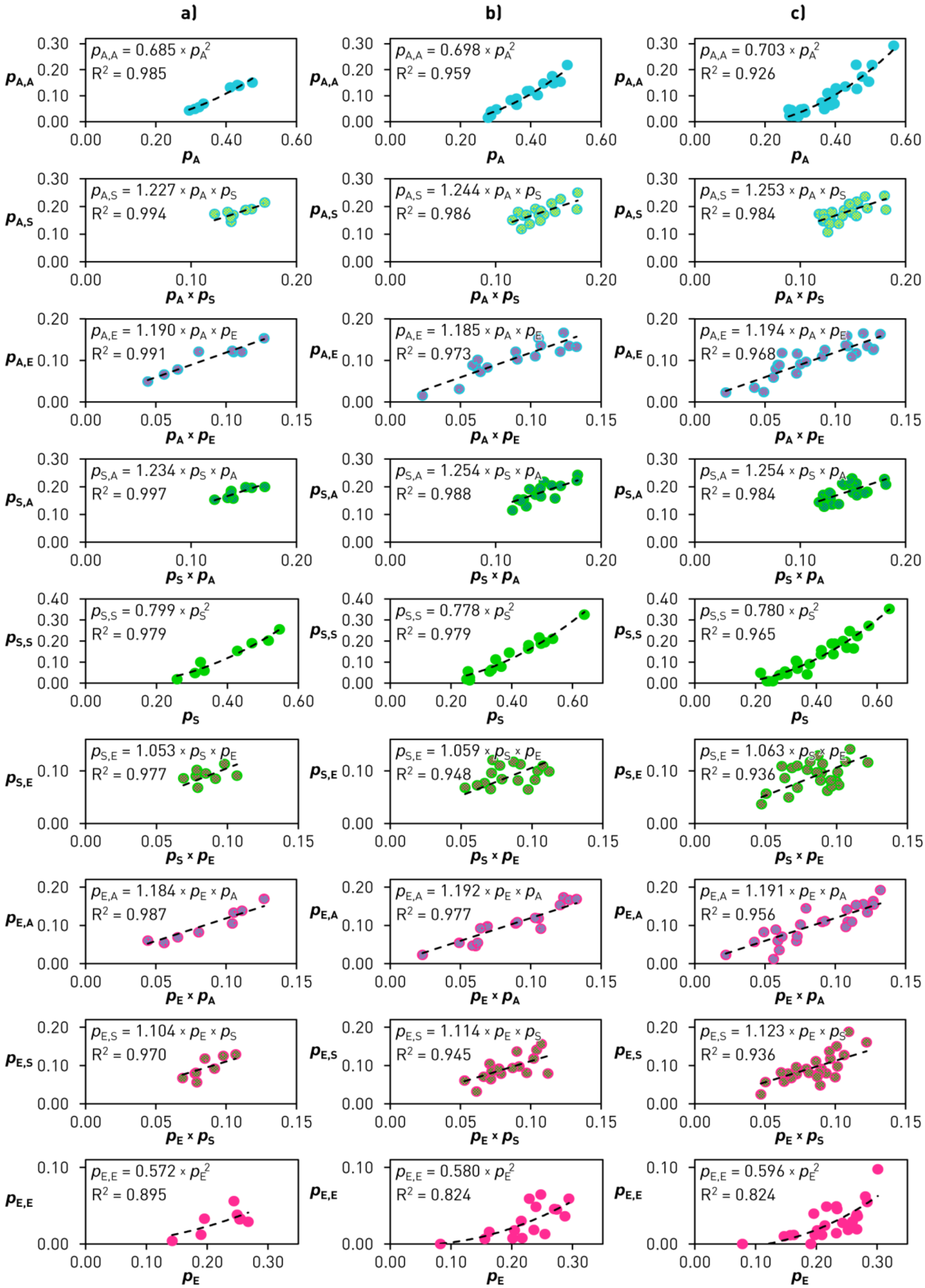

Figure 5.2 Relations between proportions of sequences of two design operations as dependent variables and proportions of design operations as independent variables: a) total activities; b) activities split into two parts; c) activities split into three parts

Proportion of synthesis to analysis sequences – A multiple linear regression was calculated to predict the proportion of moves from synthesis to analysis based on the interaction of proportions of synthesis and proportion of analysis design operations. A significant regression equation (Equation 5.12) was found ($F(1,23)=1384$, $p<0.000$) with an $R^2=0.984$. The interaction significantly predicted the proportion of synthesis to analysis sequences ($\beta=0.992$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.938$, $p=0.145$).

$$p_{\mathrm{S,A}} = 1.254 \cdot p_{\mathrm{S}} \cdot p_{\mathrm{A}} \qquad \text{(Equation 5.12)}$$

Proportion of synthesis to synthesis sequences – A simple linear regression was calculated to predict the proportion of moves from synthesis to synthesis based on the squared proportion of synthesis design operation. A significant regression equation (Equation 5.13) was found ($F(1,23)=630.3$, $p<0.000$) with an $R^2=0.965$. The squared proportion significantly predicted the proportion of synthesis to synthesis sequences ($\beta=0.982$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.965$, $p=0.562$).

$$p_{\mathrm{S,S}} = 0.780 \cdot p_{\mathrm{S}}^2 \qquad \text{(Equation 5.13)}$$

Proportion of synthesis to evaluation sequences – A multiple linear regression was calculated to predict the proportion of moves from synthesis to evaluation based on the interaction of proportions of synthesis and proportion of evaluation design operations. A significant regression equation (Equation 5.14) was found ($F(1,23)=335.1$, $p<0.000$) with an $R^2=0.936$. The interaction significantly predicted the proportion of synthesis to evaluation sequences ($\beta=0.967$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.953$, $p=0.318$).

$$p_{\mathrm{S,E}} = 1.063 \cdot p_{\mathrm{S}} \cdot p_{\mathrm{E}} \qquad \text{(Equation 5.14)}$$

Proportion of evaluation to analysis sequences – A multiple linear regression was calculated to predict the proportion of moves from evaluation to analysis based on the interaction of proportions of evaluation and proportion of analysis design operations. A significant regression equation (Equation 5.15) was found ($F(1,23)=495$, $p<0.000$) with an $R^2=0.956$. The interaction significantly predicted the proportion of evaluation to analysis sequences ($\beta=0.978$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.991$, $p=0.998$).

$$p_{\mathrm{E,A}} = 1.191 \cdot p_{\mathrm{E}} \cdot p_{\mathrm{A}} \qquad \text{(Equation 5.15)}$$

Proportion of evaluation to synthesis sequences – A multiple linear regression was calculated to predict the proportion of moves from evaluation to synthesis based on the interaction of proportions of evaluation and proportion of synthesis design operations. A significant regression equation (Equation 5.16) was found ($F(1,23)=333.6$, $p<0.000$) with an $R^2=0.936$. The interaction significantly predicted the proportion of evaluation to analysis sequences ($\beta=0.967$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.983$, $p=0.943$).

$$p_{\mathrm{E,S}} = 1.123 \cdot p_{\mathrm{E}} \cdot p_{\mathrm{S}} \qquad \text{(Equation 5.16)}$$

Proportion of evaluation to evaluation sequences – A simple linear regression was calculated to predict the proportion of moves from evaluation to evaluation based on the squared proportion of evaluation design operation. A significant regression equation (Equation 5.17) was found ($F(1,23)=107.8$, $p<0.000$) with an $R^2=0.824$. The squared proportion significantly predicted the proportion of evaluation to evaluation sequences ($\beta=0.908$, $p<0.000$). However, the Shapiro-Wilk test rejected the normality assumption at the significance level of 0.05 ($W=0.910$, $p=0.034$). Again, the issue of non-normal error distribution is addressed in Section 5.3.

$$p_{\mathrm{E,E}} = 0.596 \cdot p_{\mathrm{E}}^2 \qquad \text{(Equation 5.17)}$$

The aforementioned equations enable modelling of proportions of nine possible sequences of two ASE design operations based on three independent variables. The response provided by the equations can be used to perform moving average analysis of ASE design operations sequences as shown in Figure 4.11 and gain qualitative insights into patterns of performing ASE design operations throughout differently set up team conceptual design activities. Nevertheless, the normality of residuals assumption has been violated for two of the models; hence these models have not been directly implemented in further developments. More information on the implementation and the ability of the formulated linear regression models to reflect ASE design operation sequences captured in the protocol analysis study is also investigated in Section 5.3.

5.2.2. Sequences of problem- and solution-related design operations

Following is linear regression modelling of sequences of two design operations aggregated into problem- and solution-related. Symbolically, this relationship can be written as shown in Equations 5.18 and 5.19. In the case of sequences of problem- and solution-related design operations, linear regression has been performed for three cases (Figure 5.3): the complete protocol strings (8 data points), protocol strings split into two fragments (16 data points), and protocol strings split into three fragments (24 data points).

$$p_{\mathrm{x,x}} = k_{\mathrm{x,x}} \cdot p_{\mathrm{x}}^2 , \qquad \mathrm{x} = \{\mathrm{PRO;SOL}\} \qquad \text{(Equation 5.18)}$$

$$p_{\mathrm{x,y}} = p_{\mathrm{y}} - p_{\mathrm{y,y}} = k1_{\mathrm{x,y}} \cdot p_{\mathrm{y}}^2 + k2_{\mathrm{x,y}} \cdot p_{\mathrm{y}} , \ \mathrm{x} = \{\mathrm{PRO;SOL}\}, \ \mathrm{y} = \{\mathrm{PRO;SOL}\} \qquad \text{(Equation 5.19)}$$

The results again confirm the assumption of consistent relationships, with differences in-between the three cases of linear regression ranging from 0.8% to 3.5%. Since two coefficients have been used to model moves from problem to solution space and from solution to problem space, these proportions can be calculated simply by subtracting proportion of moves from problem space to problem space from the proportion of problem-related design operations, and subtracting proportion of moves from solution space to solution space from the proportion of solution-related design operation respectively (as shown in the first part of Equation 5.19). The relationships described hereafter concern the linear regression analysis using 24 data points.

Proportion of problem space to problem space sequences – A simple linear regression was calculated to predict the proportion of moves from problem space to problem space based on the squared proportion of problem-related design operation. A significant regression equation (Equation 5.20) was found ($F(1,23)=980.5$, $p<0.000$) with an $R^2=0.977$. The squared proportion significantly predicted the proportion of problem- to problem-related design operation sequences ($\beta=0.988$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.957$, $p=0.389$).

$$p_{\mathrm{PRO,PRO}} = 1.581 \cdot p_{\mathrm{PRO}}^2 \qquad \text{(Equation 5.20)}$$

Proportion of problem space to solution space sequences – A multiple linear regression was calculated to predict the proportion of moves from problem space to solution space based on the product of the proportion of problem-related and the proportion of solution-related design operations. A significant regression equation (Equation 5.21) was found ($F(2,22)=234.1$, $p<0.000$) with an $R^2=0.955$. Both the squared proportion ($\beta=-2.143$, $p<0.000$) and the proportion ($\beta=3.044$, $p<0.000$) significantly predicted the proportion of problem- to solution-related design operation sequences. Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.951$, $p=0.288$).

$$p_{\mathrm{PRO,SOL}} = -0.337 \cdot p_{\mathrm{SOL}}^2 + 0.394 \cdot p_{\mathrm{SOL}} \qquad \text{(Equation 5.21)}$$

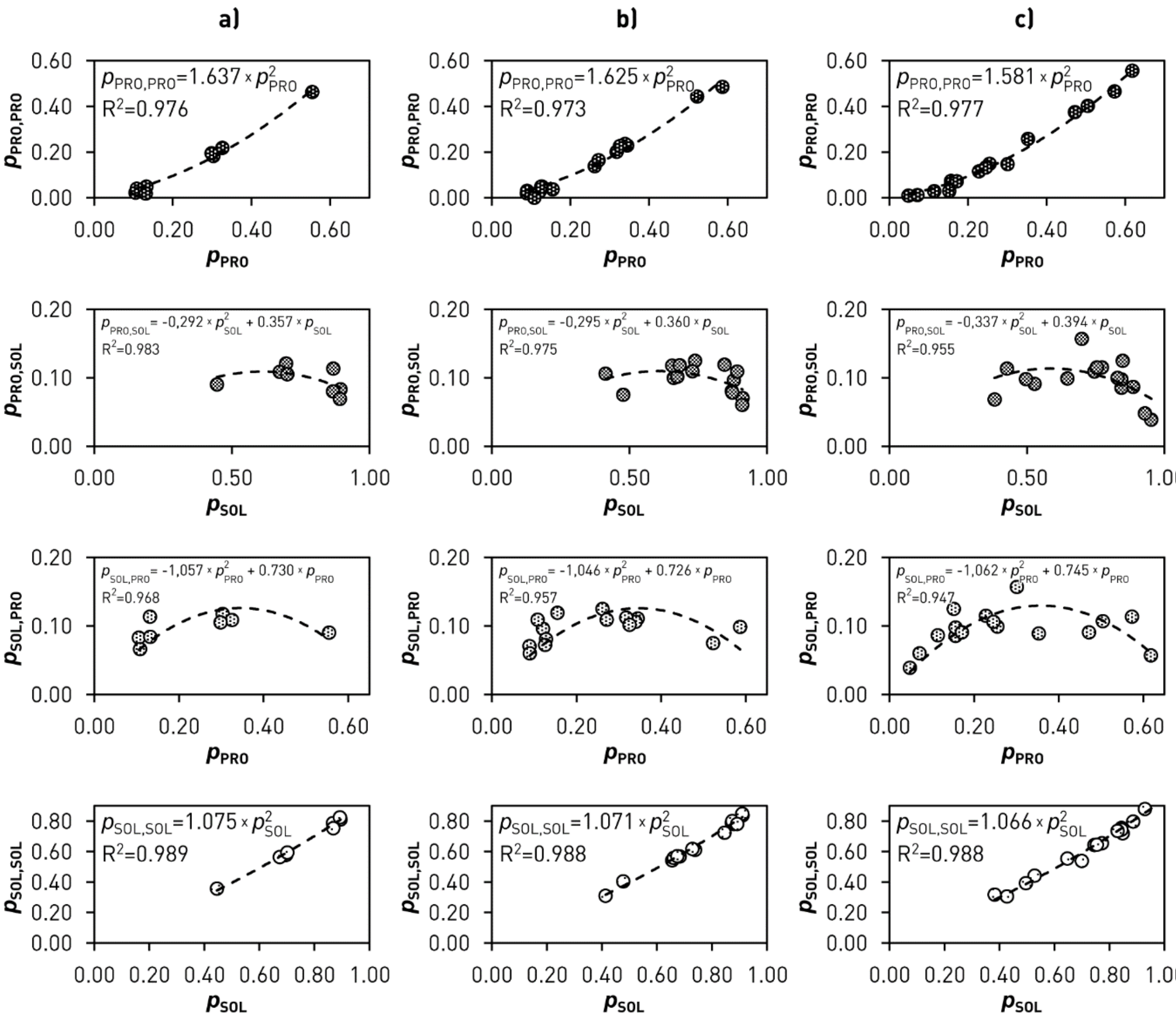

Figure 5.3 Relations between proportions sequences of problem and solution-related design operations as dependent variables and proportions of problem- and solution-related design operations as independent variables:

a) total activities; b) activities split into two parts; c) activities split into three parts

Proportion of solution space to problem space sequences – A multiple linear regression was calculated to predict the proportion of moves from solution space to problem space based on the product of the proportion of solution-related and the proportion of problem-related design operations. A significant regression equation (Equation 5.22) was found ($F(2,22)=195.5$, $p<0.000$) with an $R^2=0.947$. Both the squared proportion ($\beta=-1.432$, $p<0.000$) and the proportion ($\beta=2.186$, $p<0.000$) significantly predicted the proportion of problem- to solution-related design operation sequences. Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.967$, $p=0.593$).

$$p_{\text{SOL,PRO}} = -1.062 \cdot p_{\text{PRO}}^2 + 0.745 \cdot p_{\text{PRO}} \qquad \text{(Equation 5.22)}$$

Proportion of solution space to solution space sequences – A simple linear regression was calculated to predict the proportion of moves from solution space to solution space based on the squared proportion of solution-related design operation. A significant regression equation (Equation 5.23) was found ($F(1,23)=1949$, $p<0.000$) with an $R^2=0.988$. The squared proportion significantly predicted the proportion of solution- to solution-related design operation sequences ($\beta=0.994$, $p<0.000$). Shapiro-Wilk test failed to reject the normality assumption at the significance level of 0.05 ($W=0.922$, $p=0.064$).

$$p_{\mathrm{SOL,SOL}} = 1.066 \cdot p_{\mathrm{SOL}}^2 \qquad \text{(Equation 5.23)}$$

The above equations describe the proportions of four possible sequences of the problem- and solution-related design operations based on three independent variables. These equations enable moving average analysis of problem/solution sequences as shown in Figure 4.12 and gain qualitative insights into patterns of switching in-between the problem and the solution space throughout different configurations of team conceptual design activity. As it is the case with sequences of ASE, the ability of the formulated linear regression models to reflect problem- and solution-related design operation sequences captured in the protocol analysis study is investigated in Section 5.3.

5.2.3. Sequences of ASE within and in-between problem and solution space

Finally, linear regression modelling has also been conducted to describe sequences of ASE design operation within and in-between the problem and the solution space. In this step, the previously reported regression models of sequences of design operations aggregated into ASE and problem/solution-related are utilised as independent variables. At the core, this procedure is identical to formulating the relationships of proportions of ASE design operations in the problem and the solution space and the proportions of ASE and problem/solution-related design operations.

Hence, a hypothesised relationship is formulated as follows: proportions of moves between two ASE design operations within and in-between the problem and the solution space are proportional to the product of the corresponding proportions of moves between ASE and the proportions of moves between the problem/solution-related design operations. Symbolically, this relationship can be written as shown in Equation 5.24.

$$p_{\mathrm{xw,yz}} = k_{\mathrm{xw,yz}} \cdot p_{\mathrm{xw}} \cdot p_{\mathrm{yz}}\,, \qquad \mathrm{x,y} = \{\mathrm{PRO;SOL}\}, \quad \mathrm{w,z} = \{\mathrm{A;S;E}\} \qquad \text{(Equation 5.24)}$$

Due to a relatively large number of possible sequences, the results of the linear regression modelling have not been plotted. Instead, the equation coefficients, F-statistics, p-values and R^2 are reported in Tables 5.1 and 5.2. Unlike the case with previously reported models, linear regression modelling has been conducted using only 8 data points, that is without splitting the initial protocol strings. The reason for this is that due to the smaller number of sequences, the shorter protocol strings do not contain all possible instances of sequences of two design operations, making the results unreliable.

The effect of the lower number of particular instances of design operations sequences (e.g. instances where teams moved from solution space to problem evaluation) is reflected in lower R^2 values of the corresponding equations in Tables 5.1 and 5.2. For example, no significant equations were found for the proportions of moves from solution synthesis to problem evaluation and from solution evaluation to problem evaluation (p-value > 0.05).

Table 5.1 Linear regression models of sequences of two ASE design operations within and in-between problem and solution space

Equation (including coefficient)	F-statistic	p-value	R^2
$p_{PA,PA} = 1.239 \cdot p_{PRO,PRO} \cdot p_{A,A}$	F(1,7) = 55.39	p<0.001**	0.888
$p_{PA,PS} = 0.978 \cdot p_{PRO,PRO} \cdot p_{A,S}$	F(1,7) = 403.9	p<0.000**	0.983
$p_{PA,PE} = 1.374 \cdot p_{PRO,PRO} \cdot p_{A,E}$	F(1,7) = 467.6	p<0.000**	0.985
$p_{PA,SA} = 1.478 \cdot p_{PRO,SOL} \cdot p_{A,A}$	F(1,7) = 25.33	p<0.005**	0.784
$p_{PA,SS} = 1.834 \cdot p_{PRO,SOL} \cdot p_{A,S}$	F(1,7) = 60.03	p<0.001**	0.897
$p_{PA,SE} = 0.597 \cdot p_{PRO,SOL} \cdot p_{A,E}$	F(1,7) = 8.014	p<0.050*	0.534
$p_{PS,PA} = 1.023 \cdot p_{PRO,PRO} \cdot p_{S,A}$	F(1,7) = 179.6	p<0.000**	0.963
$p_{PS,PS} = 0.790 \cdot p_{PRO,PRO} \cdot p_{S,S}$	F(1,7) = 144.8	p<0.000**	0.954
$p_{PS,PE} = 1.262 \cdot p_{PRO,PRO} \cdot p_{S,E}$	F(1,7) = 229.7	p<0.000**	0.970
$p_{PS,SA} = 0.213 \cdot p_{PRO,SOL} \cdot p_{S,A}$	F(1,7) = 10.98	p<0.050*	0.611
$p_{PS,SS} = 1.613 \cdot p_{PRO,SOL} \cdot p_{S,S}$	F(1,7) = 53.78	p<0.001**	0.885
$p_{PS,SE} = 0.499 \cdot p_{PRO,SOL} \cdot p_{S,E}$	F(1,7) = 4.583	p>0.050	0.396
$p_{PE,PA} = 1.228 \cdot p_{PRO,PRO} \cdot p_{E,A}$	F(1,7) = 182.8	p<0.000**	0.963
$p_{PE,PS} = 0.717 \cdot p_{PRO,PRO} \cdot p_{E,S}$	F(1,7) = 333	p<0.000**	0.979
$p_{PE,PE} = 0.413 \cdot p_{PRO,PRO} \cdot p_{E,E}$	F(1,7) = 11.92	p<0.050*	0.630
$p_{PE,SA} = 0.514 \cdot p_{PRO,SOL} \cdot p_{E,A}$	F(1,7) = 43.75	p<0.001**	0.862
$p_{PE,SS} = 1.048 \cdot p_{PRO,SOL} \cdot p_{E,S}$	F(1,7) = 9.729	p<0.050*	0.582
$p_{PE,SE} = 0.785 \cdot p_{PRO,SOL} \cdot p_{E,E}$	F(1,7) = 19.11	p<0.005**	0.732

* p<0.05 ** p<0.01

Table 5.2 Linear regression models of sequences of two ASE design operations within and in-between problem and solution space (continued)

Equation (including coefficient)	F-statistic	p-value	R^2
$p_{SA,PA} = 1.578 \cdot p_{SOL,PRO} \cdot p_{A,A}$	$F(1,7) = 60.16$	$p<0.001$**	0.896
$p_{SA,PS} = 1.156 \cdot p_{SOL,PRO} \cdot p_{A,S}$	$F(1,7) = 38.44$	$p<0.001$**	0.846
$p_{SA,PE} = 0.157 \cdot p_{SOL,PRO} \cdot p_{A,E}$	$F(1,7) = 8.3$	$p<0.050$*	0.543
$p_{SA,SA} = 0.876 \cdot p_{SOL,SOL} \cdot p_{A,A}$	$F(1,7) = 473.4$	$p<0.000$**	0.985
$p_{SA,SS} = 0.896 \cdot p_{SOL,SOL} \cdot p_{A,S}$	$F(1,7) = 506.4$	$p<0.000$**	0.986
$p_{SA,SE} = 1.121 \cdot p_{SOL,SOL} \cdot p_{A,E}$	$F(1,7) = 872.7$	$p<0.000$**	0.992
$p_{SS,PA} = 0.844 \cdot p_{SOL,PRO} \cdot p_{S,A}$	$F(1,7) = 57.01$	$p<0.001$*	0.891
$p_{SS,PS} = 0.953 \cdot p_{SOL,PRO} \cdot p_{S,S}$	$F(1,7) = 142.7$	$p<0.000$**	0.953
$p_{SS,PE} = 0.140 \cdot p_{SOL,PRO} \cdot p_{S,E}$	$F(1,7) = 2.73$	$p>0.050$*	0.281
$p_{SS,SA} = 1.129 \cdot p_{SOL,SOL} \cdot p_{S,A}$	$F(1,7) = 1441$	$p<0.000$**	0.995
$p_{SS,SS} = 0.975 \cdot p_{SOL,SOL} \cdot p_{S,S}$	$F(1,7) = 220.8$	$p<0.000$**	0.969
$p_{SS,SE} = 1.103 \cdot p_{SOL,SOL} \cdot p_{S,E}$	$F(1,7) = 712.6$	$p<0.000$**	0.990
$p_{SE,PA} = 1.716 \cdot p_{SOL,PRO} \cdot p_{E,A}$	$F(1,7) = 40.96$	$p<0.001$**	0.854
$p_{SE,PS} = 1.595 \cdot p_{SOL,PRO} \cdot p_{E,S}$	$F(1,7) = 28.83$	$p<0.005$**	0.805
$p_{SE,PE} = 0.452 \cdot p_{SOL,PRO} \cdot p_{E,E}$	$F(1,7) = 1.34$	$p>0.050$*	0.161
$p_{SE,SA} = 0.977 \cdot p_{SOL,SOL} \cdot p_{E,A}$	$F(1,7) = 658.7$	$p<0.000$**	0.990
$p_{SE,SS} = 0.967 \cdot p_{SOL,SOL} \cdot p_{E,S}$	$F(1,7) = 279.5$	$p<0.000$**	0.976
$p_{SE,SE} = 1.141 \cdot p_{SOL,SOL} \cdot p_{E,E}$	$F(1,7) = 152.5$	$p<0.000$**	0.956

* $p<0.05$ ** $p<0.01$

The 36 regression equations enable myriads of investigations to be performed and are, as such, particularly valuable addition to the mathematical model. Among other things, the response provided by the equations can be used to perform moving average analysis of ASE design operations sequences within and in-between the problem and the solution space, as shown in Figures 4.13 and 4.14. Nevertheless, the Shapiro-Wilk test rejected the assumption of normality for a total of eight design operations sequences ($p_{PA,SA}$, $p_{PA,SS}$, $p_{PS,PS}$, $p_{PE,PS}$, $p_{PE,PE}$, $p_{SS,PE}$, $p_{SE,PS}$, $p_{SE,PE}$). These regression models have thus not been directly implemented in the mathematical model. The ability of the formulated regression models to replicate the most important sequences of design operations, captured in the protocol analysis study, is investigated in the following section.

5.3. Mathematical model testing

The formulated linear regression equations enable prediction of average proportions design operations during a fragment of design activity, based on the average proportions of analysis, synthesis and evaluation, and problem- and solution-related design operations during that period. Their integration within theoretical framework proposed in Chapter 3 allows the development of a mathematical model which enables calculation of design operations datasets based on the three input parameters (two to define proportions of ASE and one to define proportions of the problem/solution-related design operations).

The mathematical model has thus been designed to rely both on the regression equations with a high goodness of fit (high R^2 values), which do not violate the normality of residuals assumption (based on the Shapiro-Wilk test), as well as the theoretical foundations of state-transitions proportions and sequences proposed in Tables 3.2 and 3.3. For example, regarding proportions of design operations, solution analysis, synthesis and evaluation exhibit higher R^2 values when compared to problem analysis, synthesis and evaluation. Hence, according to Table 3.2, problem analysis, synthesis and evaluation can be defined as shown in Equations 5.25, 5.26 and 5.27.

$$p_{\mathrm{PA}} = p_{\mathrm{A}} - p_{\mathrm{SA}} \quad \text{(Equation 5.25)}$$

$$p_{\mathrm{PS}} = p_{\mathrm{S}} - p_{\mathrm{SS}} \quad \text{(Equation 5.26)}$$

$$p_{\mathrm{PE}} = p_{\mathrm{E}} - p_{\mathrm{SE}} \quad \text{(Equation 5.27)}$$

In this way, the high goodness of fit of solution-related design operation is utilised to improve the prediction ability of problem-related design operations. Moreover, such formulation ensures that the resulting proportions of ASE precisely correspond to the input parameters.

Similarly, it can be argued that for a protocol string with a sufficient number of design operation instances, the following expressions apply (Equations 5.28, 5.29, 5.30, 5.31 and 5.32):

$$p_{\mathrm{A}} = p_{\mathrm{A,A}} + p_{\mathrm{A,S}} + p_{\mathrm{A,E}} = p_{\mathrm{A,A}} + p_{\mathrm{S,A}} + p_{\mathrm{E,A}} \quad \text{(Equation 5.28)}$$

$$p_{\mathrm{S}} = p_{\mathrm{S,A}} + p_{\mathrm{S,S}} + p_{\mathrm{S,E}} = p_{\mathrm{A,S}} + p_{\mathrm{S,S}} + p_{\mathrm{E,S}} \quad \text{(Equation 5.29)}$$

$$p_{\mathrm{E}} = p_{\mathrm{E,A}} + p_{\mathrm{E,S}} + p_{\mathrm{E,E}} = p_{\mathrm{A,E}} + p_{\mathrm{S,E}} + p_{\mathrm{E,E}} \quad \text{(Equation 5.30)}$$

$$p_{\mathrm{PRO}} = p_{\mathrm{PRO,PRO}} + p_{\mathrm{PRO,SOL}} = p_{\mathrm{PRO,PRO}} + p_{\mathrm{SOL,PRO}} \quad \text{(Equation 5.31)}$$

$$p_{\mathrm{SOL}} = p_{\mathrm{SOL,PRO}} + p_{\mathrm{SOL,SOL}} = p_{\mathrm{PRO,SOL}} + p_{\mathrm{SOL,SOL}} \quad \text{(Equation 5.32)}$$

Namely, the proportion of a particular design operation is equal to the sum of proportions of all design operations sequences starting with that specific design operation, but also to the sum of proportions of all design operations sequences ending with that design operation. Such argumentation is vital as it allows taking advantage of only the regression equations with the highest prediction ability.

Hence, the resulting set of equations encompassed within the mathematical model results either from regression modelling or from the theoretical assumptions. The mathematical model developed in such a way was first employed to compute moving average proportions of design operations and sequences of design operations for a given average ASE and problem/solution proportions. Namely, to test the prediction ability of the developed mathematical model, the input parameters have been sampled from the moving average proportions of ASE and problem/solution-related design operations obtained from the protocol analysis study of team conceptual design activities.

The predictive power of the model was tested by plotting graphs of moving average proportions corresponding to those reported in Figures 4.9-4.13. Only the three predicated independent variables have been sampled from the original dataset. The mathematical model thus samples these three independent variables from the observed moving-average data to compute proportions of design operations and their sequences for these particular moving-average windows. The resulting graphs concerning the proportions of ASE design operations within the problem and the solution space are shown in Figure 5.4. The graphs concerning the proportions of sequences of two ASE design operations are shown in Figure 5.5. Finally, the graphs concerning the proportions of sequences of two design operations related to either problem or solution space are shown in Figure 5.6.

A qualitative comparison reveals a high level of resemblance between the observation-based Figures 4.9, 4.11 and 4.12, and the simulation-based Figures 5.4, 5.5 and 5.6. Notably, it can be argued that the simulated proportions coincide with the descriptions of the teams' processes provided in Subsection 4.3.3. The change in proportions of design operations and their sequences, which have been identified for each of the teams, have been satisfactorily replicated using the formulated mathematical model. Since the conceptualisation of the mathematical model as a support tool is to provide insights regarding the patterns and trends in performing particular design operations, rather than precise percentages, the model has been validated as appropriate for further research steps.

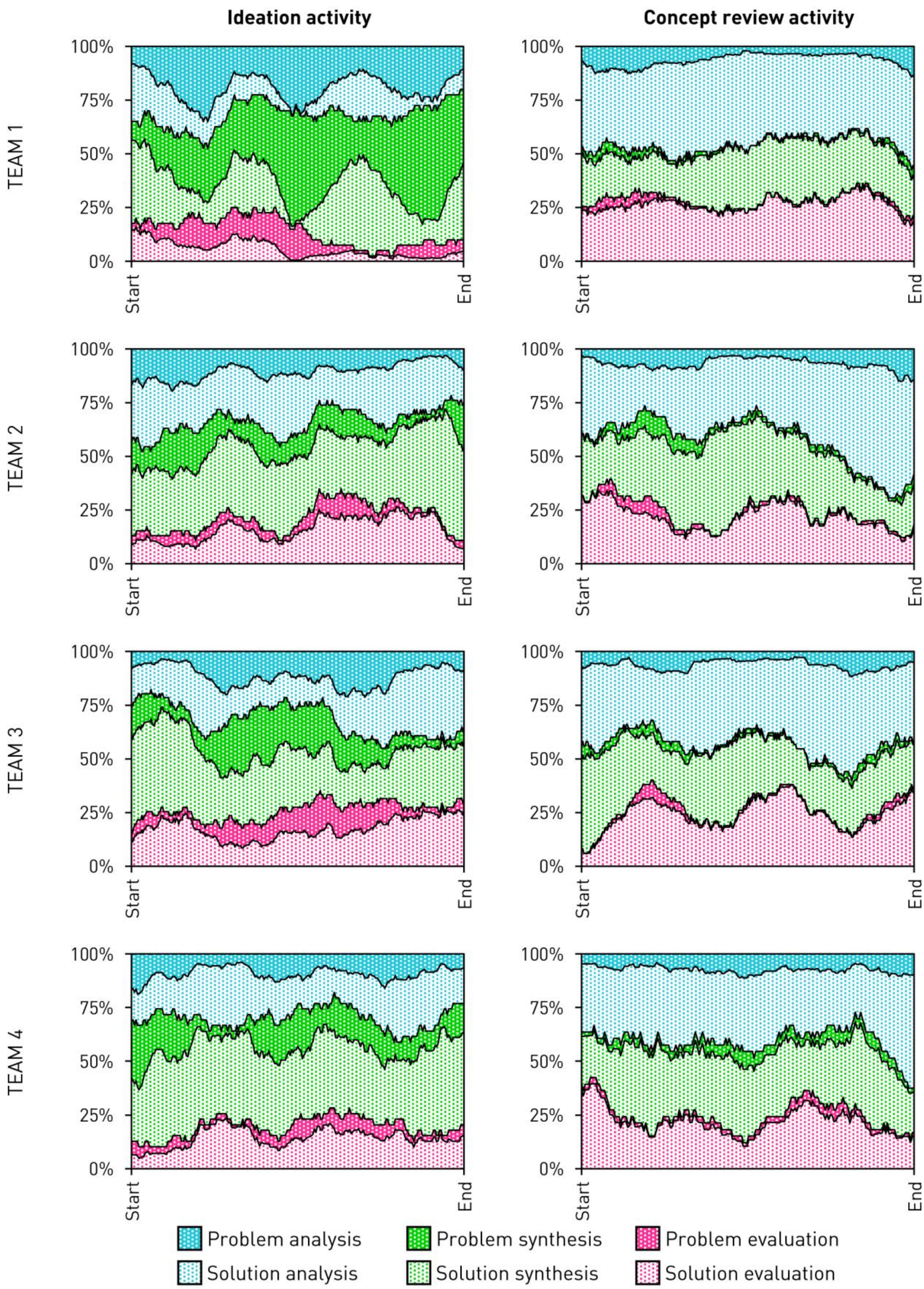

Figure 5.4 Overview of simulated moving average proportions of design operations with input parameters based on observed ideation and concept review activities

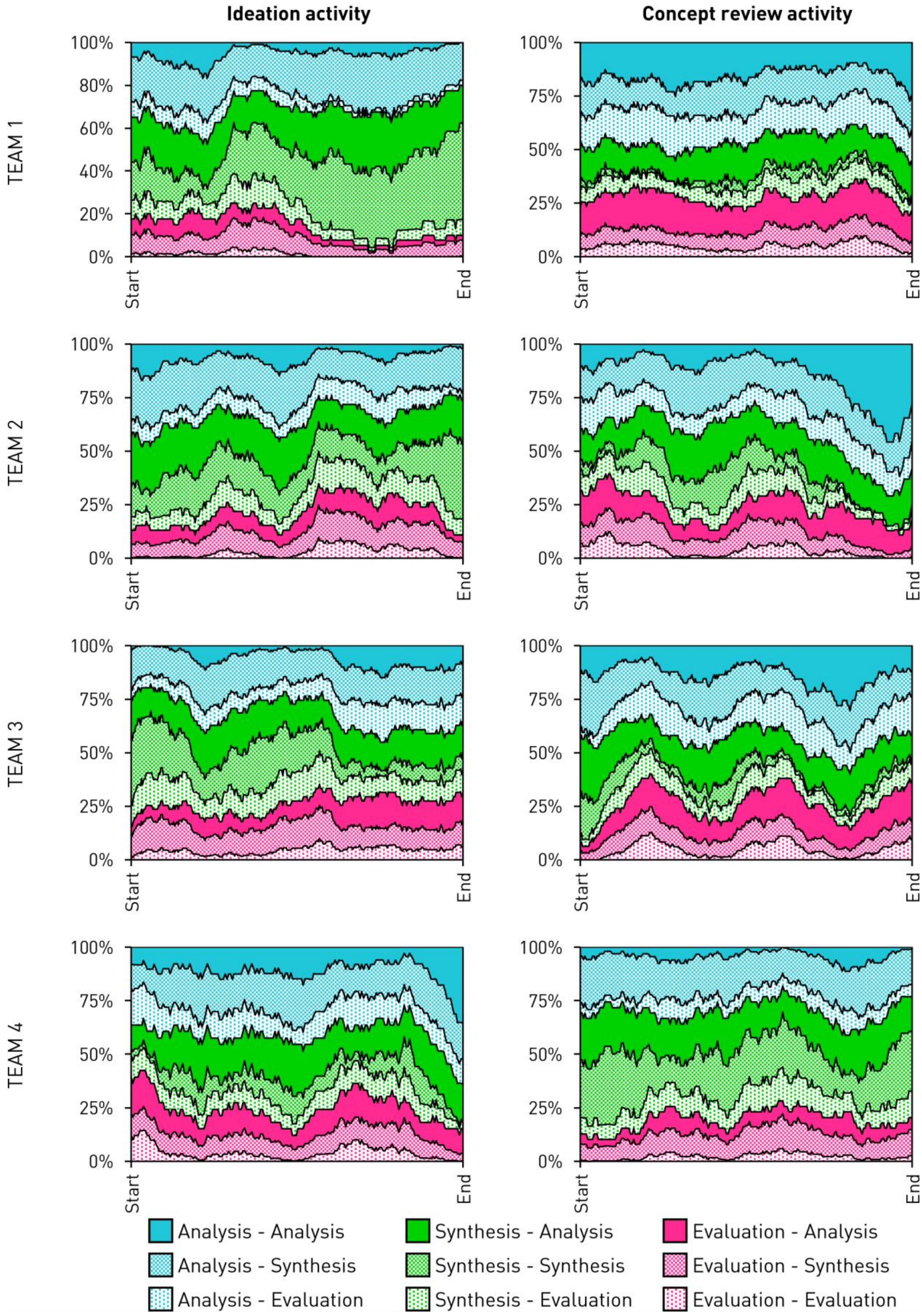

Figure 5.5 Overview of simulated moving average proportions of sequences of ASE with input parameters based on observed ideation and concept review activities

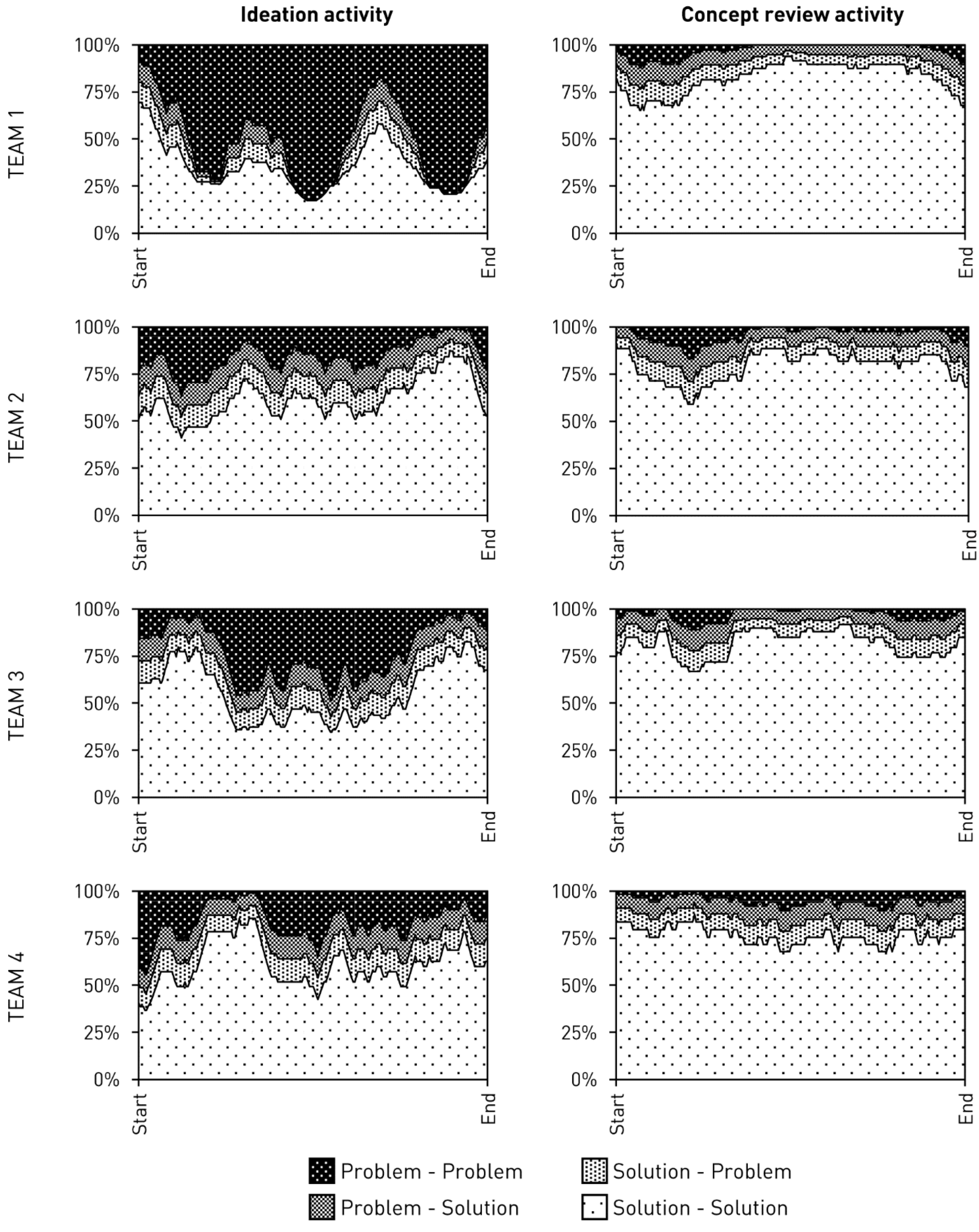

Figure 5.6 Overview of simulated moving average proportions of sequences of problem- and solution-related design operations with input parameters based on observed ideation and concept review activities

Finally, a comparison can be made for sequences of unaggregated design operations (ASE within and in-between the problem and the solution space). Again, due to a large number of combinations of observed experimental sessions and sequences of two design operations, only one example per team is here reported (Figure 5.7).

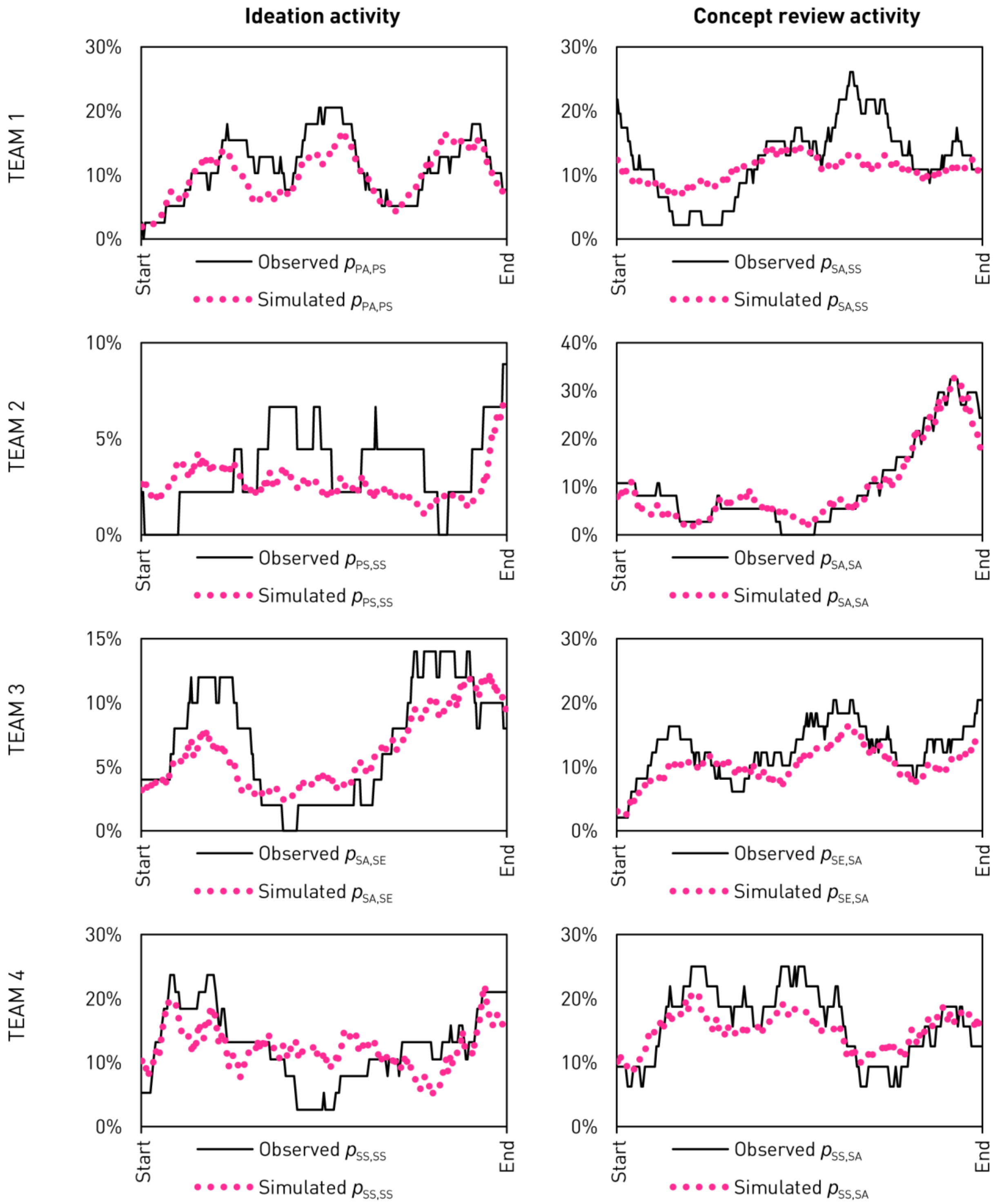

Figure 5.7 Overview of simulated moving average proportions of sequences of ASE design operations within and in-between problem and solution space, and with input parameters based on observed ideation and concept review activities

Each of the examples represents the moving average proportion of a distinctive sequence which exhibited high proportions during the observed activities. The lower fit of the regression models is noticeable, particularly for sequences which have rarely appeared during the protocol analysis study. Also, the regression models fail to reflect the spikes precisely, that is the major changes in moving average proportions of certain design operations sequences appearing in-between a relatively small number of protocol segments. Nevertheless, the changes in proportions of sequences have to a large degree been satisfactorily replicated using the mathematical model.

6. COMPUTATIONAL STUDY

The sixth chapter reports on the second experimental study. The mathematical model formulated in the previous chapter is here utilised as a means of simulating proportions and sequences of design operations, based on a predefined setup of team conceptual design process. A computational tool has been developed for this purpose, and a computational study has been set up in order to investigate the effects of design novelty and the progress of conceptual design stage on the team conceptual design activity process. The approach to the analysis of simulated protocols is based on the protocol analysis reported in the fourth chapter.

The mathematical model developed in Chapter 5 transforms any given proportion of ASE and the ratio of the problem- and solution-related design operations into proportions of ASE design operations within and in-between the problem and the solution space, as well as proportions of moves between two of such design operations. In this chapter, the predictive power of the mathematical model is utilised to simulate experimental datasets describing proportions and sequences of design operations which are characteristic for team conceptual design process in technical systems development. In order to conduct such experimental studies, a computational tool which utilises the mathematical model has been developed.

The computational tool and the integrated mathematical model enable simulations of scenarios outside the scope of covered through the protocol analysis study reported in Chapter 4. More precisely, the research question RQ5 concerns identifying the differences in the way teams perform design operations depending on the novelty of the technical system being designed. Of particular research interest is identifying process differences in the conceptual design activities of the adaptive versus innovative design projects. Insights from the literature review reported across Sections 2.1-2.3 have been used to set up the overall features of the process expected during the conceptual design stage of technical system development.

The tool developed for conducting the computational study is described in Section 6.1. The adaptive and innovative design setups for the computational study of the conceptual design are described in Section 6.2. Finally, in Section 6.3, the simulated protocols are analysed in terms of design operation proportions and sequences.

6.1. Computational tool

An Excel-based computational tool has been developed to enable efficient utilisation of the mathematical model as a means of simulating information processing during team conceptual design activity. The computational tool facilitates predefinition of computational study parameters, running plentiful simulations of stochastic processes, and analysis of the resulting protocol strings. The description of the algorithm used to implement the mathematical model in the computational tool is shown in Figure 6.1.

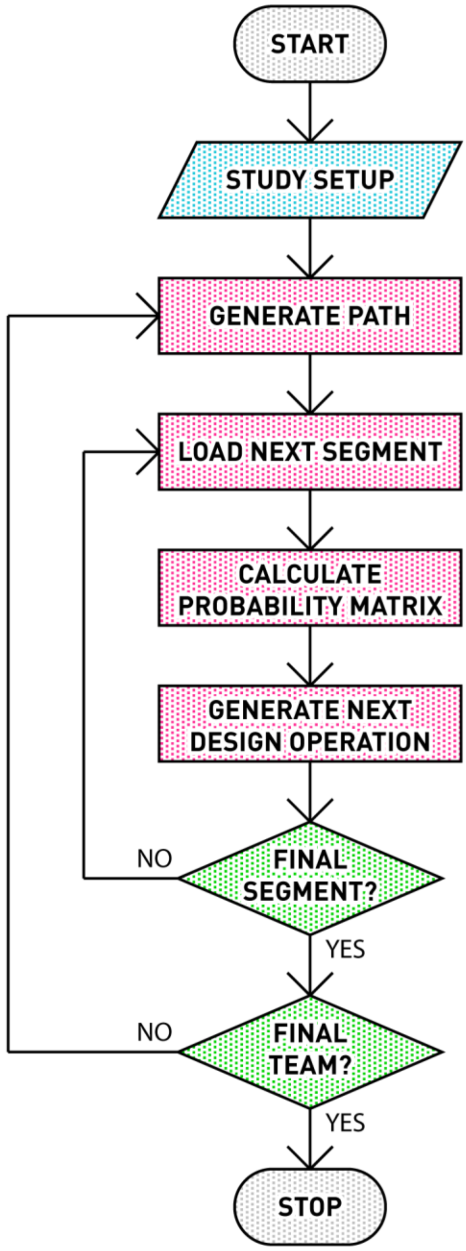

Figure 6.1 The algorithm used to implement the mathematical model for the computational study of team conceptual design process

The main steps within the algorithm can be described as follows:

1. **Study setup** – The user predefines several computational study parameters. First, the number of simulations run (number of teams simulated) and the minimal number of steps (without iteration) are defined. Second, the steps of the conceptual design process are characterised by assigning each of the steps in the process with a certain proportion of ASE and problem/solution-related design operations. An example of predefining the conceptual design steps is shown in Figure 6.2.

STEP		A	S	E	PRO	SOL
	S1	60%	30%	10%	60%	40%
	S2	35%	50%	15%	40%	60%
	S3	10%	60%	30%	20%	80%
	S4	40%	20%	40%	30%	70%
	S5	35%	40%	25%	15%	85%

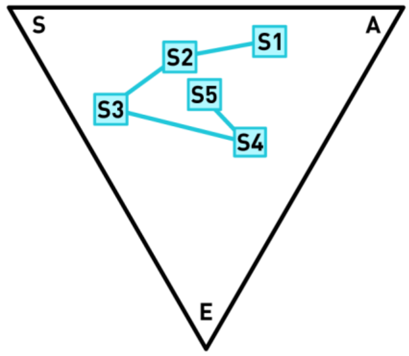

Figure 6.2 An example of defining the conceptual design process path using proportions of ASE design operations in steps S1, S2, S3, S4 and S5

Finally, the level of iteration and uncertainty are defined, since both phenomena have been found critical for distinguishing adaptive and innovative design within the literature review. As shown in Figure 6.1, study setup is the only algorithm step where the user provides an any type of input.

2. **Generate path** – The progress of the conceptual design stage stems from the predefined steps and the assigned proportions of ASE and problem/solution ratio. The algorithm linearly adjusts the proportions of design operations in-between the predefined steps of the conceptual design process, thus building initial linear paths between the steps (as shown in triangular proportion visualisation in Figure 6.2). Additionally, the total number of predefined protocol segments is equally distributed across the designated process path. The linear path and the number of segments along the path are then subject to changes based on the predefined levels of iteration and uncertainty. Namely, iteration and uncertainty are conceptualised as a distortion of the linear progress. In the context of here presented research, iteration is defined as a probability of returning to a previous point in the process (repeating design operations). Before moving from one design operations to another, the probability of iteration is compared to a randomly generated number. If the random number is lower than the iteration probability, the process will continue at a

random, previously visited combination of ASE proportions (for the purpose of here presented computational study, the process went back up to 15 path steps). Uncertainty distorts the vector length *r* and angle δ (Figure 3.6) assigned to the proportions of ASE in the current process. The vector's length is modified based on the inverse of the normal cumulative distribution for the predefined vector length and a standard deviation. The standard deviation defines the level of uncertainty – the higher the standard deviation, the higher the probability that the vector length will be more distorted. The same procedure is then repeated with the angle of the vector and the proportion of problem-related design operations. Once the vector is distorted, the proportions of ASE design operations are recalculated. The effect of various levels of iteration and uncertainty on the progress of the simulated conceptual design is shown in Figure 6.3.

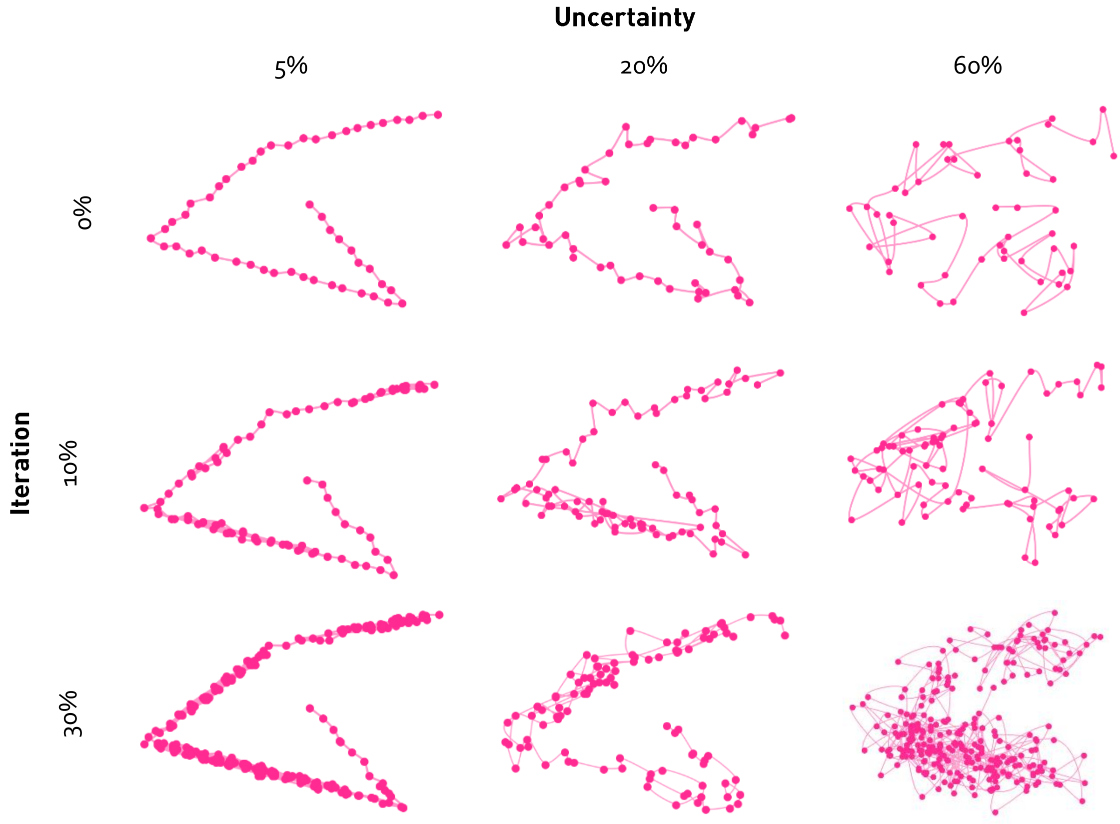

Figure 6.3 The effect of different levels of iteration and uncertainty on the conceptual design process path

3. **Load next segment** – Once the path has been generated and the final number of segments is known, the simulation then moves from one segment to another and loads the proportions of ASE and problem/solution-related design operations assigned to each of these segments. This cycle is repeated until the last predefined segment is reached, as shown in Figure 6.1.

4. **Calculate probability matrix** – After loading the parameters for a particular segment, the regression models described in Section 5.2 are used to calculate (predict) proportions of sequences of ASE design operations within and in-between the problem and the solution space. Thus, given any set of segments containing average proportions of ASE (e.g. paths visualised in triangular proportion visualisation as shown in Figure 4.10), and the corresponding problem/solution ratios, the expected proportions of design operations and their sequences are computed. These proportions are transformed into probabilities of moves between design operations (within a probability matrix), as proposed within Equation 3.4 and Tables 3.4 and 3.5 within the theoretical framework (Chapter 3).
5. **Generate next design operation** –The computed probability matrix is used to generate the next design operation based on the current one. The following design operation is thus selected by emulating a stochastic process (a random number is generated and compared to the probabilities in the transition matrix). When the following design operation is selected, it is written down in the protocol string, and the simulation process continues to the next segment.

Algorithm steps 3, 4 and 5 are repeated for every segment of the predefined path. The generation of new protocol instances continues until the number of path steps reaches the predefined number (path steps repeated through iteration are not counted). Algorithm step 2 is repeated for every new team simulated. An example of the simulation procedure is shown in Figure 6.4.

STEP	A	S	E	PRO	SOL
1	60%	30%	10%	60%	40%
2	35%	50%	15%	40%	60%
3	10%	60%	30%	20%	80%
4	40%	20%	40%	30%	70%
5	35%	40%	25%	15%	85%

PATH STEPS	ITERATION PROBABILITY	UNCERTAINTY LEVEL
200	5%	30%

TOTAL STEPS	TOTAL ITERATIONS	WINDOW SIZE
280	11	15%

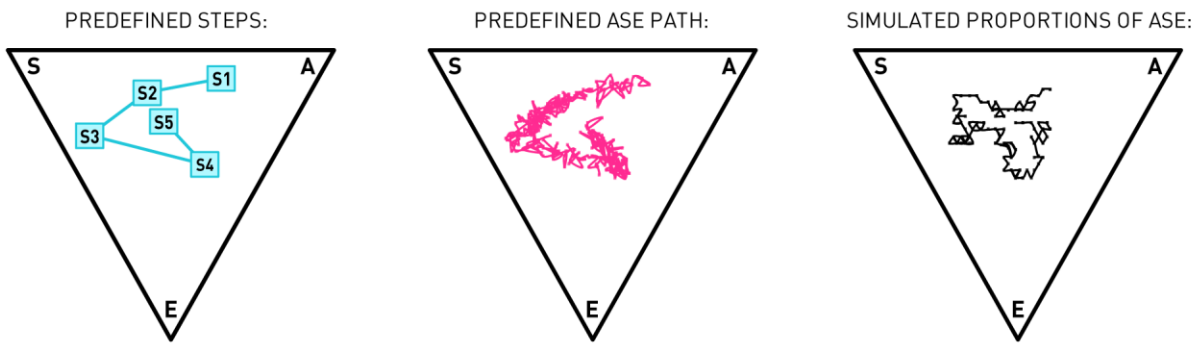

Figure 6.4 Simulation procedure example. Triangular visualisations include predefined conceptual design steps, predefined ASE path which defines transition probabilities, and actual simulated proportions of ASE

6.2. Computational study setup

The overall structure of the simulated conceptual design process has been developed based on the information-processing decomposition of the conceptual design stage as found within the prescriptive models of engineering design. The rationale for utilising systematic design guidelines stems from the argument that prescriptive design methodologies, such as the Systematic Approach by Pahl and Beitz can, to some degree, be employed as predictive models of engineering design. Namely, Kannengiesser and Gero [258] report that although the Systematic Approach is generally seen as a prescriptive model of designing, it can be used to predict some (but not all) of students' design issue behaviour.

The overview of information processes associated with the conceptual design stage has been provided in Section 2.2. Five conceptual design steps (Table 6.1) have been defined analogously to the problem-solving steps prescribed in Table 2.5 and described throughout the Subsection 2.2.2: problem formulation, solution search, solution generation, solution evaluation and solution refinement.

Table 6.1 Predifined conceptual design steps implemented in the computational study

COMPUTATIONAL STUDY STEPS	PRESCRIPTIVE DESIGN STEPS	ASE DESIGN OPERATIONS	PROBLEM AND SOLUTION SPACE
S1 Problem formulation	**Function structure development**	Analysis and synthesis	Problem-solution co-evolution
S2 Solution search	**Working principles search**		
S3 Solution generation	**Concept generation**	Synthesis	Solution space
S4 Solution evaluation	**Concept evaluation**	Analysis and evaluation	Problem and solution space
S5 Solution refinement	**Concept selection and refinement**	Synthesis and evaluation	Problem and solution space

Problem formulation concerns analysis of the existing requirements and formulation of new ones, whereas teams simultaneously search for new solutions as part of the problem-solution co-evolution process. Solution generation involves primarily the synthesis design operation within the solution space, solution evaluation concerns gaining understanding solution entities and evaluating them against the entities of the problem space. Finally, during the last step, teams refine the selected solution and conduct the final evaluation of its elements.

Each of the steps can be further assigned to the distinctive characteristics of adaptive and innovative design. The overview of the relevant innovative and adaptive design characteristics and how they are implemented in the context of state transition using ASE design operations within and in-between the problem and the solution space is shown in Table 6.2.

Table 6.2 Overview of adaptive and innovative design characteristics and how they have been implemented in the computational study

CHARACTERISTICS	ADAPTIVE DESIGN		INNOVATIVE DESIGN	
	Literature	Implementation	Literature	Implementation
Conceptual design uncertainty [44], [175]	Medium	**Medium deviation** from the planned path within the triangular proportion visualisation	Large	**High deviation** from the planned path within the triangular proportion visualisation
Iteration [120]	Less	**Lower iteration probability** within the planned path	More	**Higher iteration probability** within the planned path
Function decomposition [41]	Existing solutions	Higher proportions of **solution analysis**	Abstract problem formulation	Higher proportions of **problem synthesis**
Use of existing solution elements [172]	Reuse of priori solution elements	Higher proportions of **solution evaluation**	No or little priori solutions elements	Higher proportions of **solution synthesis**
Proficiency of evaluation criteria usage [8]	Higher	Higher proportions of **solution evaluation**	Lower	Lower proportions of **solution evaluation**
Nature of exploration [135]	Less exploratory	Lower proportions of **synthesis**	More exploratory	Higher proportions of **synthesis**
Customer-driven [135]	More	Higher proportions of **problem analysis**	Less	Higher proportions of **problem synthesis and evaluation**
Dominant type of reasoning [176]	Inductive reasoning	Higher proportions of **evaluation**	Abductive reasoning	Higher proportions of **synthesis**

The insights from the literature are conceptualised as constraints for the scope of the parameters used for calculating the moving average proportions of design operations and their sequences. For example, as shown in Tables 2.3 and 2.6, the innovative (original/radical) design is characterised by more iteration and information processing, fuzzy front-end activities, lower proficiency in using evaluation criteria, more exploration, no or little prior given solution elements, as well as higher levels of conceptual design uncertainty. On the other hand, the adaptive (incremental) design is characterised by more process flexibility, abbreviated front end activities, higher proficiency of evaluation criteria usage, more customer-driven development and partial reuse of prior solutions. Innovative design is related to abductive design processes and design synthesis, whereas adaptive design is related to inductive design processes and design evaluation. In addition, innovative designs are based on requirements lists and abstract problem formulation, whereas adaptive designs are based on the analysis of existing products.

Each characteristic affects the predefined proportions of ASE and problem/solution-related design operations, as well as on the structure of the conceptual design process when visualised using the triangular proportion visualisation. An overview of the exact mechanisms used to implement and simulate these characteristics has been described in the previous section.

6.2.1. Adaptive design computational study setup

The input parameters for the computational study of adaptive conceptual design are reported in Table 6.3. Overall, the iteration probability is set to low (5%), and the uncertainty level is set to medium (40%). Problem formulation is associated with high proportions of analysis and problem-related design operations since it is more customer driven (analysis of given requirements).

Table 6.3 Overview of input parameters for adaptive design computational study (p_E is derived from p_A and p_S, and p_{SOL} is derived from p_{PRO})

STEP	p_A	p_S	p_E	p_{PRO}	p_{SOL}	ITERATION PROBABILITY	UNCERTAINTY LEVEL
S1 Problem formulation	60%	30%	10%	60%	40%	5%	40%
S2 Solution search	50%	40%	10%	30%	70%		
S3 Solution generation	30%	45%	25%	15%	85%		
S4 Solution evaluation	35%	15%	50%	30%	70%		
S5 Solution refinement	40%	35%	25%	20%	80%		

Solution search is characterised by a high proportion of analysis within the solution space (analysis of existing solutions) and relatively low proportions of synthesis (not explorative). Solution evaluation is defined using high proportions of evaluation and even proportion of problem and solution-related design operations (higher proficiency of evaluation criteria usage, inductive reasoning). Finally, the solution refinement step exhibits high proportions of synthesis and evaluation of solutions.

6.2.2. Innovative design computational study setup

The input parameters for the computational study of innovative conceptual design are reported in Table 6.4. The iteration probability and uncertainty level are significantly higher (10% and 80% respectively) when compared to the adaptive design setup. Since problem formulation is less customer-driven, the first step is associated with similar proportions of analysis, synthesis and evaluation, as teams need to analyse the given problem but also formulate and evaluate new requirements. In addition, the proportions of the problem- and solution-related design operations are set even, as co-evolution is expected due to more exploratory nature of the process.

Table 6.4 Overview of input parameters for innovative design computational study (p_E is derived from p_A and p_S, and p_{SOL} is derived from p_{PRO})

STEP	p_A	p_S	p_E	p_{PRO}	p_{SOL}	ITERATION PROBABILITY	UNCERTAINTY LEVEL
S1 Problem formulation	45%	35%	20%	70%	30%	10%	80%
S2 Solution search	25%	60%	15%	40%	60%		
S3 Solution generation	30%	45%	25%	25%	75%		
S4 Solution evaluation	35%	25%	40%	40%	60%		
S5 Solution refinement	35%	45%	20%	30%	70%		

Solution search is characterised by exploration, and higher proportions of synthesis, particularly within the solution space as low no or little prior given solution elements are used. The proportion of synthesis and problem-related design operations slowly declines towards solution generation. Solution evaluation has a relatively low proportion of evaluation when compared to adaptive processes, due to lower proficiency in using evaluation criteria. Solution refinement step is defined similarly to the adaptive design, with values adjusted towards synthesis and problem space.

6.2.3. Comparison of adaptive and innovative computational study setups

A visual comparison of ASE proportions within the five predefined conceptual design steps of the adaptive and innovative computational study is shown in Figure 6.5. It is important to highlight that real-world adaptive and innovative design processes may exhibit significantly different proportions of design operations than described in Tables 6.3 and 6.4. The provisionally selected values are based primarily on the characteristics that the design process is likely to inherit from the novelty level of the technical system being developed, and which have been identified in the conducted literature review. The proportions are also based on the proportions identified in the protocol analysis study, primarily by relating solution search to ideation activity and solution evaluation and refinement to concept review activity.

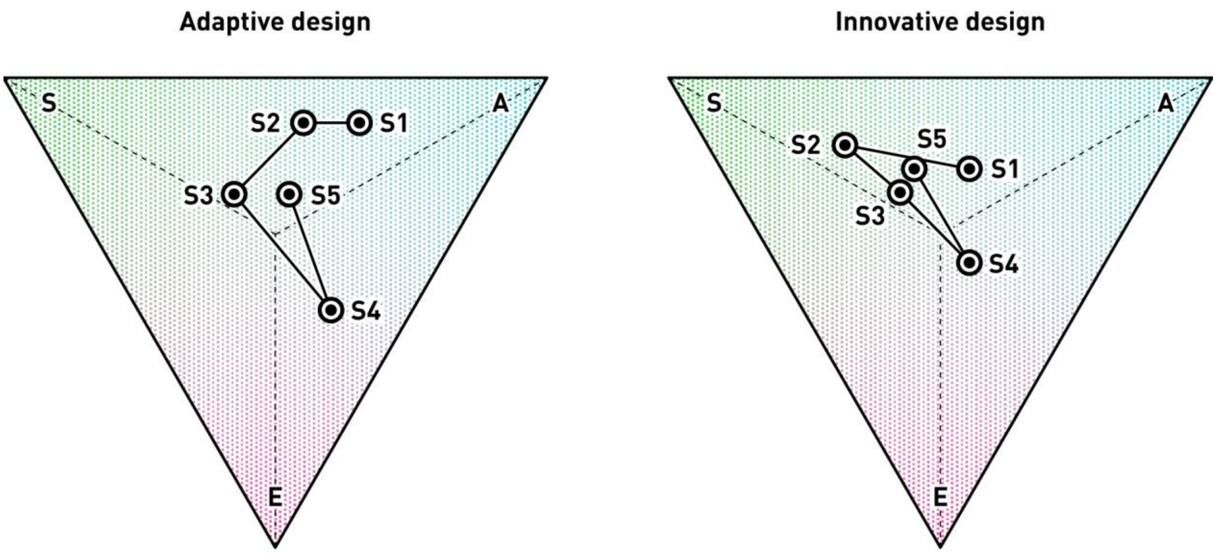

Figure 6.5 Triangular visualisation of ASE design operation proportions for the predefined steps of the computational study of adaptive and innovative conceptual design process

It is assumed that the selected values of input parameters will induce distinctive patterns of change in proportions and sequences of design operations during when comparing adaptive and innovative design.

6.3. Computational study results

Similar to the protocol analysis study, the outputs of the computational simulations have been analysed in terms of proportions of design operations and their sequences, and how these proportions change with the progress of the conceptual design stage. The results of the conceptual design simulations within the context of the adaptive and innovative design of technical systems are from here on regarded as adaptive and innovative design processes. A single (test case) computational experiment study has been conducted with both the adaptive and innovative setup simulated 100 times. The initial number of steps (without iteration) has been set to 300 and the first design operation has been set to “problem analysis”.

On average, 541 (SD=73) steps have been simulated per team during adaptive design, and 1734 (SD=687) per team during innovative design. Hence, the higher iteration rate has resulted in a significant increase in the number of steps performed during the innovative conceptual design. The absolute frequencies of each of the design operations and their aggregation to ASE problem-solution spaces during types of processes are available in Table 6.5.

Table 6.5 Absolute frequencies of instances of protocol codes during simulations of adaptive and innovative conceptual design process

FREQUENCY VARIABLE	ADAPTIVE		INNOVATIVE	
	Mean	**SD**	**Mean**	**SD**
Problem analysis (n_{PA})	65.52	16.2	194.01	96.5
Problem synthesis (n_{PS})	42.09	10.6	204.96	96.7
Problem evaluation (n_{PE})	35.94	9.0	128.01	66.8
Solution analysis (n_{SA})	139.49	26.0	339.04	176.7
Solution synthesis (n_{SS})	129.5	23.4	467.48	233.6
Solution evaluation (n_{SE})	121.56	24.4	278.88	159.3
Analysis (n_{A})	205.01	37.3	533.05	263.5
Synthesis (n_{S})	171.59	30.3	672.44	322.1
Evaluation (n_{E})	157.5	31.2	406.89	221.8
Problem-related (n_{PRO})	143.55	31.6	526.98	254.5
Solution-related (n_{SOL})	390.55	66.7	1085.4	560.6
Total of ASE in problem and solution space (n)	**521.47**	**72.7**	**1734.26**	**686.9**

Moreover, the effect of the iteration rate is also visible in the disproportionate increase in the standard deviation of the number of instances assigned to each design operation. Examples of the simulation steps in terms of change in ASE proportions are shown in Figure 6.6.

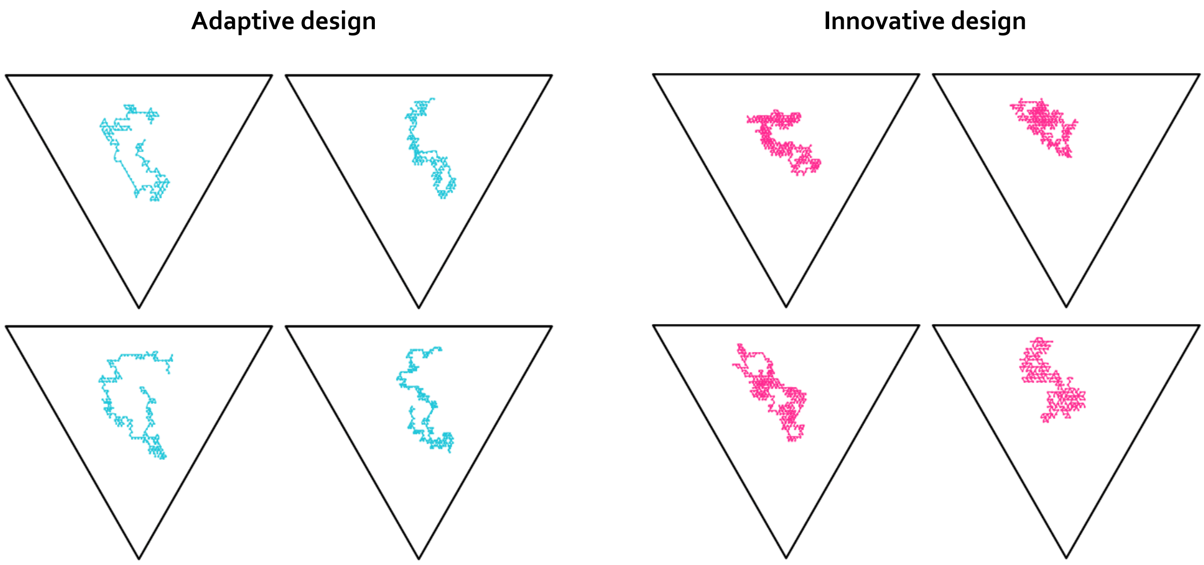

Figure 6.6 Examples of visualising average proportions of ASE for steps within adaptive and innovative design simulations

6.3.1. Simulated proportions of design operation

The distribution of the counted instances of design operation was normalised, so further analyses could be conducted using proportions of design operations. The resulting distribution of design operation proportions during adaptive and innovative conceptual design processes are shown in Table 6.6.

Table 6.6 Proportions of protocol codes obtained from adaptive and innovative conceptual design simulations

PROPORTION VARIABLE	ADAPTIVE		INNOVATIVE	
	Mean	SD	Mean	SD
Problem analysis (p_{PA})	0.123	0.020	0.122	0.027
Problem synthesis (p_{PS})	0.079	0.014	0.131	0.026
Problem evaluation (p_{PE})	0.067	0.011	0.079	0.013
Solution analysis (p_{SA})	0.261	0.018	0.208	0.019
Solution synthesis (p_{SS})	0.243	0.022	0.292	0.035
Solution evaluation (p_{SE})	0.228	0.024	0.168	0.032
Analysis (p_{A})	0.384	0.019	0.330	0.020
Synthesis (p_{S})	0.322	0.023	0.423	0.041
Evaluation (p_{E})	0.295	0.027	0.247	0.034
Problem-related (p_{PRO})	0.268	0.032	0.333	0.055
Solution-related (p_{SOL})	0.732	0.032	0.667	0.055

State-transition proportions during adaptive design

During the adaptive conceptual design process, the most frequent ASE design operation was analysis (on average 38% of all ASE design operations per team), followed by synthesis (32%), and evaluation (30%) as the least frequent. Of all design operations, on average 27% were performed in the problem space, and 73% in solution space. On average, the most frequent design operation in problem space was problem analysis (on average 46% of all design operations in problem space per team), followed by problem analysis (29%) and problem evaluation (25%). The most frequent design operation in solution space was solution analysis (on average 36% of all design operations in solution space per team), followed by solution synthesis (33%) and solution evaluation (31%).

State-transition proportions during innovative design

The most frequent ASE design operation during the innovative conceptual design process was synthesis (on average 42% of all ASE design operations per team), followed by analysis (33%) and evaluation (25%) as the least frequent. Of all design operations, on average one third were performed in the problem space, and two thirds in the solutions space, which is a moderate change compared to the adaptive design process. On average, the most frequent problem-space design operation was problem synthesis (on average 53% of all design operations in problem space per team) followed by problem analysis (33%) and problem evaluation (14%). The order is the same within the solution space: solution synthesis was the most frequent (on average 44% of all design operations in solution space per team), followed by solution analysis (31%) and solution evaluation (25%).

Differences in state-transition proportions between ideation and concept review activities

A triangular proportion visualisation was again developed to qualitatively compare the average proportions of ASE during the adaptive and innovative design processes (enlarged parts of the visualisations are shown in Figure 6.7). The two types of simulations run populated slightly different areas within the triangular visualisation, thus indicating gravitation towards distinctive proportions of design operations. During adaptive design, the proportions populated mainly the area around the triangle centre, with a slight shift towards analysis and synthesis (top). During innovative design, the proportions range from the centre towards the synthesis corner (top left).

Finally, the differences in proportions of ASE design operations within the problem and the solution space have been visualised using box plots (Figure 6.8). The box plots combine means and medians, quartiles, as well as minimum and maximum of the data and the outliers.

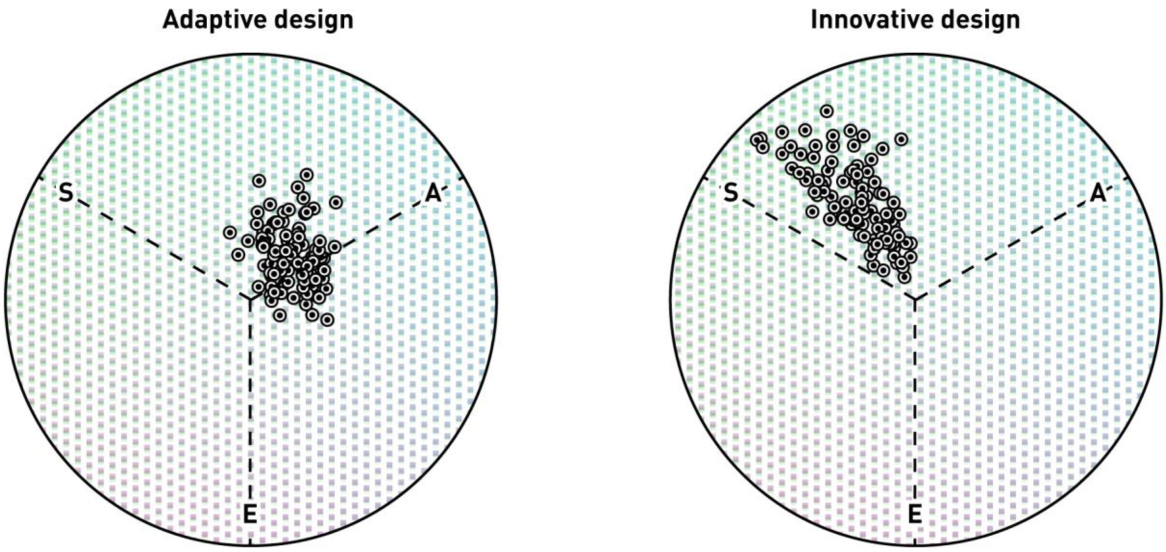

Figure 6.7 Visualisation of differences in average ASE proportions between all simulations of adaptive and innovative design

In general, the innovative design data exhibits broader interquartile ranges and more skewness (asymmetry of the probability distribution) when compared to the adaptive design data. This distinctive feature can be attributed to the higher uncertainty levels set prior to running the simulations.

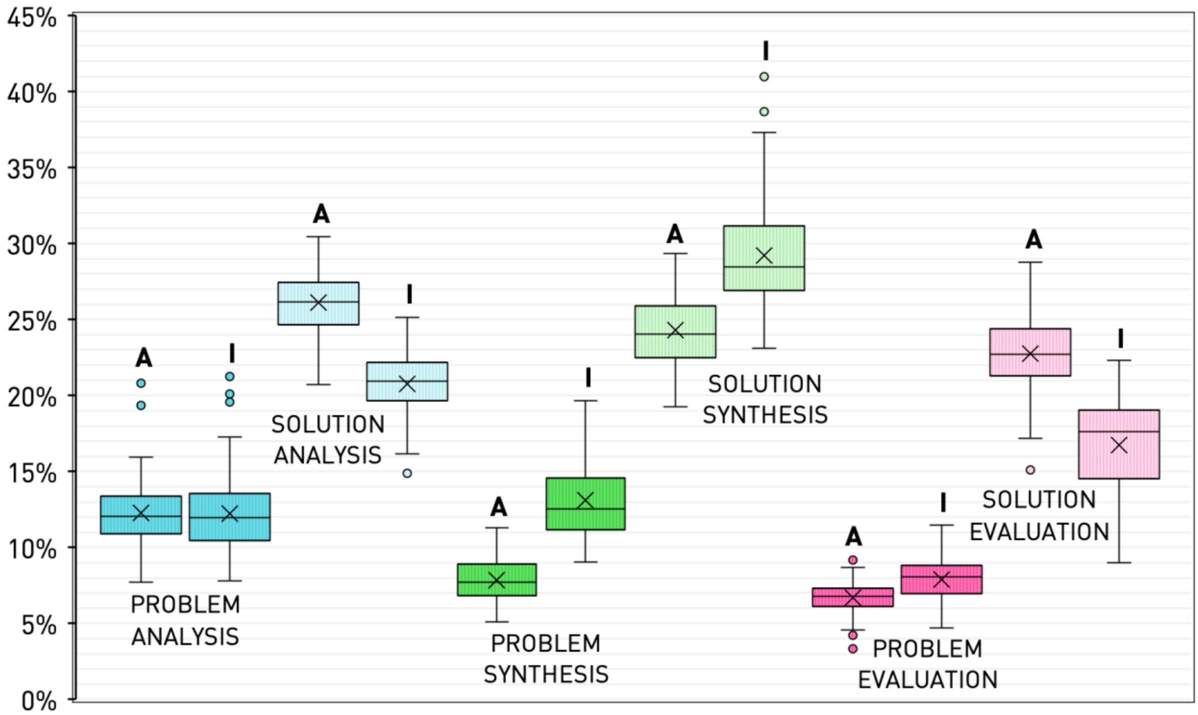

Figure 6.8 Box plot of proportions of ASE design operations within problem and solution space obtained from adaptive (A) and innovative (I) design simulations

The differences in the distributions of design operations are aligned with the characteristics for adaptive and innovative design summarised in Table 6.2 and which have been used to set up the computational experiment studies. The response characterised by the higher proportions of both problem and solution synthesis in innovative design and higher proportions of solution analysis and evaluation in adaptive design, as well as differences in steps taken, deviations in the number of instances per design operation and the proportions visualised in Figure 6.8, serves as an initial verification of the computational simulation tool (the measures of outputs are in line with the expectations based on the values of the input parameters). However, further efforts of verifying and validating the simulation tool have been omitted, since the realisation of a final computational tool is outside the scope of this thesis. The presented research instead aims at providing a theoretical and mathematical foundation for simulating team design activity.

The next subsections report on the analysis of results that could not have been simply predicted before the simulation runs – probabilities and proportions of sequences of design operations, and how they change throughout the conceptual design of innovative and adaptive technical systems development.

6.3.2. Simulated sequences of design operations

The probabilities of moves from one design operation to another have again been interpreted as probability (Markov) matrices. For each simulation run, the total number of moves between pairs of design operations have been counted and entered into the corresponding cells of the matrix. The rows of the matrix were normalised to calculate the probabilities. Each of the resulting matrices represents the probability matrix for that particular simulation run. In order to summarise the data, the probabilities matrices have been averaged per sets of adaptive and innovative design simulation runs. The resulting average probability matrices are shown in Table 6.7. Cells of the matrices are here again coloured (heat map) in order to facilitate identification of moves between design operations that are most likely to appear.

During adaptive design, the most probable design operation to come after problem analysis was solution synthesis (32.0% probability), after problem synthesis, it was problem analysis (35.1%), and after problem evaluation, it was also problem analysis (37.9%). Solution analysis was most likely to be followed by solution synthesis (35.2%), and solution synthesis and solution evaluation by solution analysis (48.3% and 31.5% respectively). As for the aggregated design operations, the most likely moves were as follows: analysis was most likely followed by synthesis (43.8%), synthesis by analysis (50.3%) and evaluation by analysis (43.0%)

Table 6.7 Averaged probabilities of moves between ASE design operations in problem and solution space (left) and aggregated to ASE (right), obtained from adaptive and innovative design simulations

ASE design operations in problem and solution space

Adaptive design simulation

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.140	0.260	0.180	0.060	0.320	0.040
PS→	0.351	0.189	0.054	0.108	0.189	0.108
PE→	0.379	0.069	0.034	0.241	0.207	0.069
SA→	0.070	0.031	0.016	0.219	0.352	0.313
SS→	0.033	0.033	0.000	0.483	0.175	0.275
SE→	0.054	0.076	0.163	0.315	0.272	0.120

Innovative design simulation

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.092	0.305	0.202	0.019	0.366	0.015
PS→	0.221	0.195	0.164	0.089	0.273	0.057
PE→	0.309	0.183	0.029	0.206	0.211	0.063
SA→	0.036	0.079	0.033	0.090	0.446	0.316
SS→	0.042	0.041	0.023	0.360	0.321	0.212
SE→	0.072	0.133	0.025	0.284	0.314	0.172

ASE design operations

Adaptive design simulation

	→A	→S	→E
A→	0.264	0.438	0.298
S→	0.503	0.248	0.248
E→	0.430	0.331	0.240

Innovative design simulation

	→A	→S	→E
A→	0.122	0.567	0.312
S→	0.379	0.389	0.232
E→	0.393	0.434	0.172

During innovative design, the most likely moves starting with each of the ASE design operations in problem and solution space were as follows: problem analysis and problem synthesis were most likely to be followed by solution synthesis (36.6% and 27.3% respectively), and problem evaluation by problem analysis (30.9%), solution analysis by solutions synthesis (44.6%), solution synthesis by solution analysis (36.0%), and solution evaluation by solution synthesis (31.4%). The most likely moves for each of the aggregated ASE design operations were as follows: analysis was most likely to be followed by synthesis (56.7%), synthesis by synthesis (38.9%) or analysis (37.9%), and evaluation by synthesis (43.4%) or analysis (39.3%).

Probability matrices of individual simulation runs can be multiplied with the corresponding proportions of design operations segments in order to calculate proportions of particular moves between two design operations for that particular simulation run. The resulting proportion matrices can then be averaged per sets of adaptive and innovative design simulation runs to summarise the data. Averaged proportion matrices, which summarise the conceptual design of adaptive and innovative technical systems development, are shown in Table 6.8.

Table 6.8 Averaged proportions of moves between ASE design operations in problem and solution space (left) and aggregated to ASE (right), obtained from adaptive and innovative design simulations

Adaptive design simulation

ASE design operations in problem and solution space:

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.015	0.029	0.020	0.007	0.035	0.004
PS→	0.029	0.015	0.004	0.009	0.015	0.009
PE→	0.024	0.004	0.002	0.015	0.013	0.004
SA→	0.020	0.009	0.004	0.061	0.099	0.088
SS→	0.009	0.009	0.000	0.127	0.046	0.072
SE→	0.011	0.015	0.033	0.064	0.055	0.024

ASE design operations:

	→A	→S	→E
A→	0.103	0.171	0.116
S→	0.173	0.086	0.086
E→	0.114	0.088	0.064

Innovative design simulation

ASE design operations in problem and solution space:

	→PA	→PS	→PE	→SA	→SS	→SE
PA→	0.008	0.026	0.018	0.002	0.032	0.001
PS→	0.025	0.022	0.019	0.010	0.031	0.007
PE→	0.018	0.011	0.002	0.012	0.012	0.004
SA→	0.008	0.017	0.007	0.019	0.097	0.069
SS→	0.014	0.014	0.008	0.122	0.109	0.072
SE→	0.013	0.024	0.005	0.052	0.058	0.032

ASE design operations:

	→A	→S	→E
A→	0.037	0.172	0.095
S→	0.172	0.177	0.105
E→	0.095	0.105	0.042

To enable a qualitative comparison of the micro-scale design processes exhibited by teams engaged in adaptive and innovative design, the average proportion matrices have been mapped onto the two-dimensional state-transition model visualisation proposed in Figure 3.4. The resulting visualisation (Figure 6.9) reflects the average proportional distribution of sequences of design operations throughout the innovative and adaptive design simulations. Furthermore, the visualisation provides insight on what design operations are likely to follow once a problem or solution entity has been analysed, synthesised or evaluated. In this way, the traces of phenomena such as continuous evolution of problem and solution space, as well as problem-solution co-evolution can also be visualised. The overall thickness of the arrows entering the state nodes reflects the proportion of analysis, synthesis and evaluation during the activities.

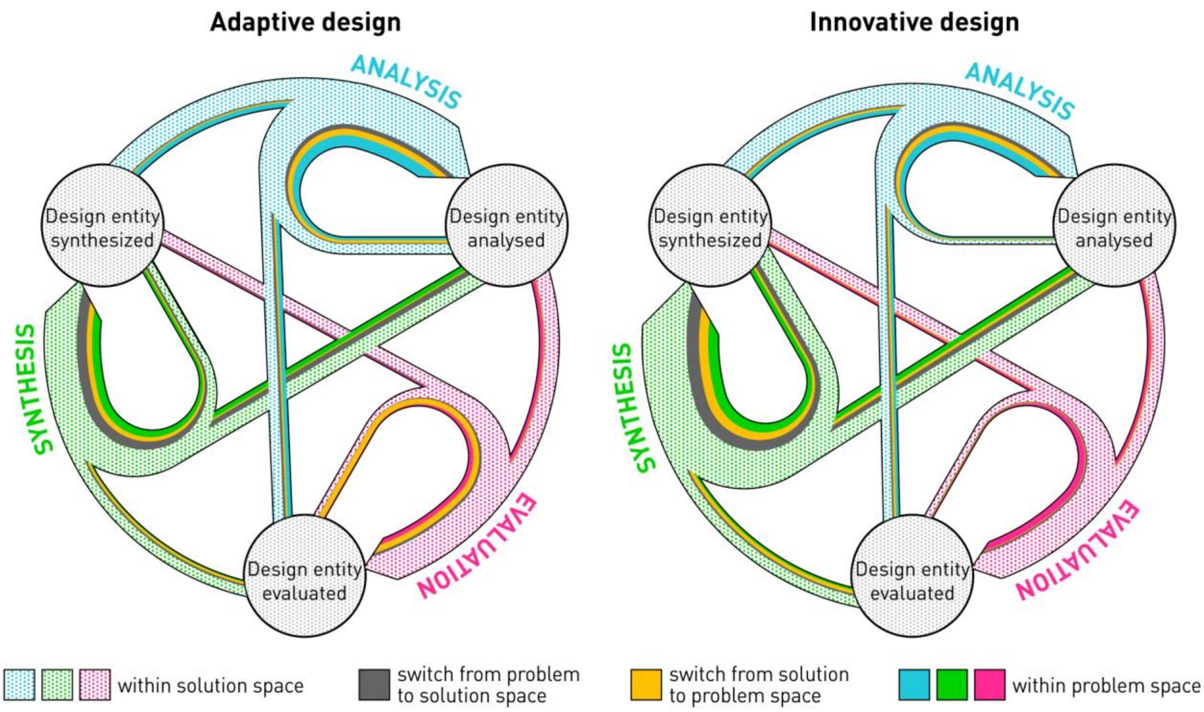

Figure 6.9 State-transition visualisation of average proportions of sequences of ASE design operations within and in-between problem and solution space during adaptive (left) and innovative (right) design simulations

Analogue to the protocol analysis study, further analysis can be conducted by taking into account sequences of three consecutive design operations, thus facilitating identification of patterns related to performing ASE design operations in the problem and the solution space. The sequences of three design operations were counted, normalised and summarised across simulation runs, thus providing average proportions of particular moves between three design operations (Table 6.9).

State-transition sequences during innovative design

The averaged proportions of moves between ASE design operations during the ideation activity (Figure 6.9 on the left, based on Table 6.8) exhibit some similarity in performing analysis, synthesis and evaluation within the problem and the solution space. The most frequent sequences of two design operations within both spaces were from analysis to synthesis and from synthesis to analysis. The moves between two analysis, two synthesis and two evaluation design operations were among the least present in both spaces. Nevertheless, the proportion of moves in problem and solution space differs largely in the case of the synthesis to evaluation sequence, which appeared primarily within the solution space.

Table 6.9 Averaged proportions of sequences of three consecutive design operations obtained from adaptive and innovative conceptual design simulations

Adaptive design

	→PA	→PS	→PE	→SA	→SS	→SE
PA→PA→	0.009	0.007	0.005	0.001	0.006	0.001
PA→PS→	0.011	0.003	0.004	0.002	0.004	0.002
PA→PE→	0.009	0.003	0.000	0.006	0.003	0.002
PA→SA→	0.001	0.000	0.000	0.001	0.002	0.002
PA→SS→	0.002	0.001	0.000	0.016	0.006	0.008
PA→SE→	0.001	0.000	0.001	0.002	0.001	0.002
PS→PA→	0.006	0.006	0.004	0.001	0.007	0.001
PS→PS→	0.003	0.001	0.001	0.001	0.002	0.001
PS→PE→	0.005	0.002	0.000	0.004	0.002	0.001
PS→SA→	0.000	0.000	0.000	0.002	0.002	0.002
PS→SS→	0.001	0.000	0.000	0.007	0.003	0.003
PS→SE→	0.001	0.001	0.001	0.003	0.003	0.002
PE→PA→	0.004	0.004	0.005	0.001	0.006	0.002
PE→PS→	0.003	0.001	0.002	0.001	0.001	0.001
PE→PE→	0.000	0.000	0.000	0.001	0.000	0.000
PE→SA→	0.001	0.001	0.001	0.003	0.005	0.009
PE→SS→	0.000	0.000	0.000	0.004	0.002	0.003
PE→SE→	0.000	0.001	0.000	0.002	0.001	0.001
SA→PA→	0.003	0.004	0.003	0.001	0.005	0.001
SA→PS→	0.004	0.002	0.003	0.001	0.003	0.002
SA→PE→	0.003	0.001	0.000	0.002	0.001	0.001
SA→SA→	0.004	0.003	0.002	0.010	0.015	0.015
SA→SS→	0.005	0.003	0.000	0.038	0.017	0.022
SA→SE→	0.006	0.006	0.008	0.029	0.021	0.021
SS→PA→	0.002	0.003	0.002	0.001	0.004	0.000
SS→PS→	0.002	0.001	0.001	0.000	0.002	0.001
SS→PE→	0.000	0.000	0.000	0.001	0.000	0.000
SS→SA→	0.006	0.007	0.003	0.021	0.038	0.032
SS→SS→	0.002	0.002	0.000	0.021	0.011	0.012
SS→SE→	0.004	0.004	0.005	0.021	0.017	0.014
SE→PA→	0.002	0.002	0.004	0.001	0.005	0.001
SE→PS→	0.004	0.001	0.003	0.001	0.002	0.003
SE→PE→	0.006	0.002	0.001	0.007	0.003	0.001
SE→SA→	0.004	0.003	0.002	0.012	0.023	0.029
SE→SS→	0.003	0.001	0.000	0.023	0.010	0.017
SE→SE→	0.003	0.003	0.005	0.016	0.012	0.015

Innovative design

	→PA	→PS	→PE	→SA	→SS	→SE
PA→PA→	0.004	0.006	0.005	0.000	0.004	0.000
PA→PS→	0.012	0.007	0.008	0.002	0.006	0.002
PA→PE→	0.011	0.006	0.001	0.005	0.002	0.003
PA→SA→	0.000	0.000	0.000	0.000	0.001	0.001
PA→SS→	0.002	0.002	0.001	0.013	0.009	0.007
PA→SE→	0.000	0.000	0.000	0.000	0.000	0.000
PS→PA→	0.007	0.012	0.009	0.001	0.011	0.000
PS→PS→	0.007	0.005	0.004	0.001	0.005	0.001
PS→PE→	0.010	0.006	0.001	0.005	0.003	0.003
PS→SA→	0.000	0.001	0.000	0.001	0.003	0.002
PS→SS→	0.002	0.002	0.000	0.009	0.008	0.005
PS→SE→	0.001	0.001	0.000	0.002	0.002	0.001
PE→PA→	0.005	0.008	0.007	0.001	0.007	0.000
PE→PS→	0.005	0.003	0.003	0.001	0.003	0.001
PE→PE→	0.001	0.000	0.000	0.001	0.000	0.000
PE→SA→	0.001	0.001	0.001	0.002	0.006	0.005
PE→SS→	0.000	0.000	0.000	0.003	0.002	0.002
PE→SE→	0.000	0.002	0.000	0.003	0.002	0.001
SA→PA→	0.001	0.003	0.002	0.000	0.003	0.000
SA→PS→	0.004	0.002	0.003	0.001	0.004	0.001
SA→PE→	0.003	0.002	0.000	0.002	0.001	0.001
SA→SA→	0.001	0.002	0.001	0.004	0.011	0.008
SA→SS→	0.005	0.004	0.002	0.033	0.024	0.019
SA→SE→	0.003	0.009	0.003	0.017	0.018	0.010
SS→PA→	0.002	0.005	0.003	0.000	0.005	0.000
SS→PS→	0.004	0.003	0.003	0.001	0.004	0.001
SS→PE→	0.001	0.001	0.000	0.001	0.001	0.001
SS→SA→	0.005	0.008	0.005	0.013	0.048	0.029
SS→SS→	0.004	0.005	0.001	0.030	0.026	0.017
SS→SE→	0.004	0.010	0.002	0.018	0.021	0.009
SE→PA→	0.001	0.002	0.002	0.000	0.004	0.000
SE→PS→	0.007	0.004	0.005	0.001	0.005	0.002
SE→PE→	0.003	0.001	0.000	0.002	0.001	0.001
SE→SA→	0.002	0.003	0.002	0.006	0.019	0.015
SE→SS→	0.003	0.003	0.001	0.019	0.014	0.012
SE→SE→	0.001	0.003	0.002	0.008	0.008	0.005

Examination of three subsequent design operations (Table 6.9) reveals the most frequent sequences within the problem space: analysis - synthesis - analysis (on average 1.1% of all sequences) as well as analysis - analysis - analysis and analysis - evaluation - analysis (both 0.9%); and within the solution space: analysis - synthesis - analysis and synthesis - analysis - synthesis (both 3.8%), followed by synthesis - analysis - evaluation (3.2%).

Regarding the moves from one space to another, teams would switch from solution to problem space mainly to perform problem analysis (on average 4.0% of all moves per team), followed by problem evaluation (3.7%) and problem synthesis (3.3%). On average, the most frequent moves from solution to problem space were from solution evaluation to problem evaluation (3.3%) followed by moves from solution analysis to problem analysis (2.0%) and solution evaluation to problem synthesis (1.5%). As for the opposite direction, when switching to the solution space, teams did it primarily to synthesise solutions (on average 6.3% of all moves per team), and less frequently to analyse (3.1%) and evaluate (1.7%) solutions. However, while problem analysis and synthesis were most frequently followed by solution synthesis when space was switched, problem evaluation was most frequently followed by solution analysis.

The probabilities of moves during the ideation activity (Table 6.7) show that once the teams switched from problem to solution space, they were very likely to stay there for the next few transitions. However, the same practice in the opposite direction was not emphasised. Adding up of proportions of design operation moves presented in Table 6.8 shows that on average 63.6% of the moves took place within the solution space, 14.2% within the problem space, and 22.1% in-between the spaces. The most frequent sequence of three design operations which led to switching from problem to solution space was: problem synthesis - problem analysis - solution synthesis (on average 0.7% of all sequences). The other way around it was: solution analysis - solution evaluation - problem evaluation (0.8%). Please consult Table 6.9 for a detailed proportional overview for sequences of three design operations.

State-transition sequences during adaptive design

Some of the observed proportions of sequences of ASE design operations during innovative design are similar, while others are fairly different in comparison to the adaptive design results (Figure 6.9 on the right, based on Table 6.8). For example, the proportions of switching spaces are similar to the adaptive design: when the teams shifted from problem to solution space during innovative design, they frequently performed also several next transitions within the solution space. On average 63.0% of the design operation moves took place within the solution space and only 14.9% within the problem space, with 22.1% of moves in-between the problem and the solution space.

The most frequent sequences of design operation within both the problem and the solution space were slightly different when compared to the adaptive design. In the problem space, the most frequent sequences were from analysis to synthesis (2.6%), from synthesis to analysis (2.5%) and from synthesis to synthesis (2.2%). The innovative design exhibited higher frequencies of moves from problem synthesis to problem evaluation (1.9%). In the solution space, the most frequent sequence was synthesis to analysis (12.2%), followed by synthesis to synthesis (10.9%) and analysis to synthesis (9.7%). Frequency of the solution analysis - solution analysis move is considerably smaller when compared to adaptive design. Nevertheless, low proportions of moves from evaluation to evaluation have been identified within both spaces (as was the case with adaptive design).

Further examination reveals that the most frequent sequences of three design operations (Table 6.9) within the solution space were synthesis – analysis - synthesis (on average 4.8% of all sequences), analysis - synthesis - analysis (3.3%), synthesis - synthesis - analysis (3.0%), and synthesis - analysis – evaluation (2.9%). As expected, due to the low proportion of problem-related moves, no frequent sequences of three design operations within the problem space can be singled out. The regular sequences of three design operations within the problem space were analysis - synthesis – analysis and synthesis - analysis - synthesis (both on average 1.2% of all sequences), as well as analysis - evaluation - analysis (1.1%) and synthesis - evaluation - analysis (1.0%);

Switching spaces somewhat differed in comparison to the adaptive design. Teams most frequently switched from solution to problem space in order to synthesise new problems (on average 5.5% of all moves per team). The other way around, teams frequently switched from problem space to solution space to perform solution synthesis (7.5%). For example, both problem analysis and problem synthesis were most frequently followed by solution synthesis once space was switched.

The most frequent sequence of three design operations which led to switching from problem to solution space was: problem synthesis - problem analysis - solution synthesis (1.1% of all sequences). The most frequent sequences from solution to problem space were solution synthesis - solution evaluation - problem synthesis (1.1%) and solution analysis - solution evaluation - problem synthesis (0.9%, see Table 6.9 for a detailed overview of sequences).

6.3.3. Simulated change in proportions throughout conceptual design

Due to a relatively large number of computational study runs in comparison to the protocol analysis study, moving average analysis of each protocol string is here impractical. Namely, moving average is more suitable the analysis of a single set of data points rather than multiple protocol strings, mainly because the simulations resulted in protocol strings of different lengths (different number of steps in the simulated processes). As an alternative to the moving average analysis, the protocol strings of each individual simulation have been divided into ten fractions of an equal number of protocol instances – from here on called deciles [55], [192]. Each decile has then been analysed in terms of proportions of design operations and their sequences as described in the previous subsections. Finally, the results have been averaged across all simulation runs for adaptive and innovative design, thus providing an overview of an average change in proportions throughout conceptual design simulation.

Three types of analyses have been performed using deciles – analysis of change in proportions of ASE design operations within the problem and the solution space (Figure 6.10); analysis of change in proportions of sequences of ASE (Figure 6.11); and analysis of change in proportions of sequences of problem- and solution-related design operations (Figure 6.12).

The change in average proportions of design operations is to a large degree in line with the setup of simulation inputs – both adaptive and innovative design processes exhibit higher proportions of problem analysis at the beginning of conceptual design, peaks of solution synthesis in the middle and a continuous increase in proportions of solution evaluation with the conceptual design progress. Nevertheless, the changes in proportions in-between deciles are more apparent during adaptive design.

Within an averaged adaptive design simulation (Figure 6.10, top), the proportions of problem synthesis and analysis drop significantly towards the middle of the process and then again slightly increase towards the end, together with problem evaluation. Solution analysis is present throughout the conceptual design, with the highest proportions at the beginning and the very end. The process exhibits a low average proportion of solution evaluation at the start; however, it increases significantly in the second half of the simulated conceptual design stage. The simulated proportions of ASE sequences during adaptive design complement the above-described patterns (Figure 6.11, top). For example, the alternation between analysis and synthesis is the highest in the first three deciles. From that point on, proportions of moves from analysis and synthesis towards evaluation, as well as the proportion of cycles of evaluation increase. In the second half, the process exhibits frequent moves from analysis to evaluation and from evaluation back to analysis, and a significant drop of moves towards synthesis. Finally, aggregating the change in proportion using problem- and solution-related design operations (Figure 6.12, top) reveals high proportions of discussing problems at the beginning and then again slight increase towards the end of conceptual design. This trend is somewhat followed by the proportions of moves in-between the problem and the solution space; however, to a significantly lesser degree.

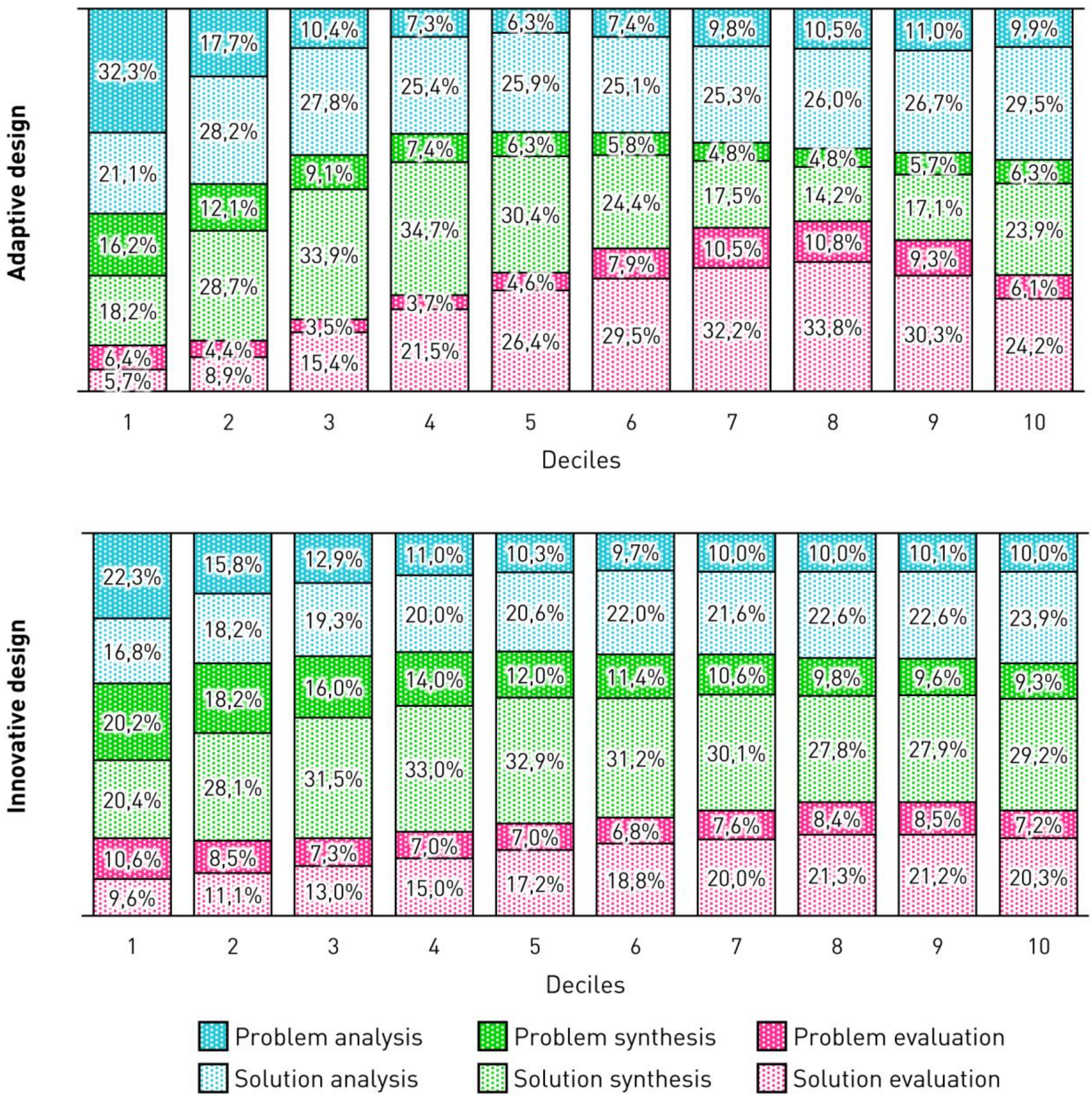

Figure 6.10 Average proportions of ASE design operations within problem and solution space across deciles of adaptive (top) and innovative (bottom) design simulations

The changes in proportions of design operations are less evident within the averaged innovative design simulation (Figure 6.10, bottom). Nevertheless, the innovative design process exhibits a noticeable peak of problem synthesis at the beginning, and solution synthesis in the middle of conceptual design simulation. The average proportion of analysis changes only slightly throughout the process. However, the ratio of problem analysis and solution analysis decreases towards the end. Overall, the average proportion of evaluation increases continuously. Nevertheless, the highest average proportion of problem analysis is in the first decile, whereas the highest average proportion of solution evaluation is in the last four deciles.

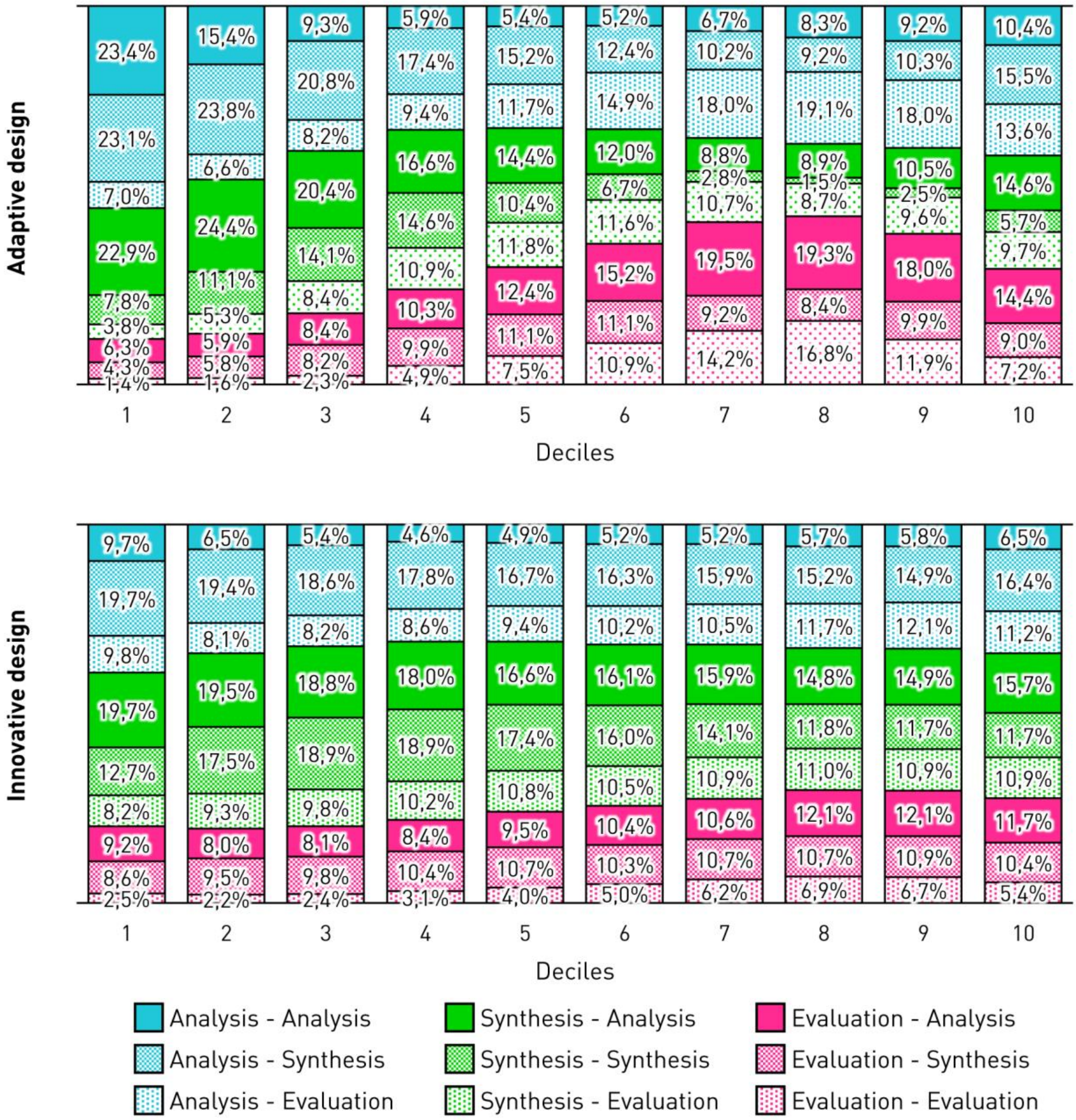

Figure 6.11 Average proportions of sequences of ASE design operations across deciles of adaptive (top) and innovative (bottom) design simulations

The alternation of analysis and synthesis design operation sequences dominates the complete averaged innovative design process, particularly at the beginning (Figure 6.11, bottom). As for sequences of a single design operation, analysis cycles are present at the beginning, synthesis cycles toward the middle, and evaluation cycles towards the end of the innovative design process.

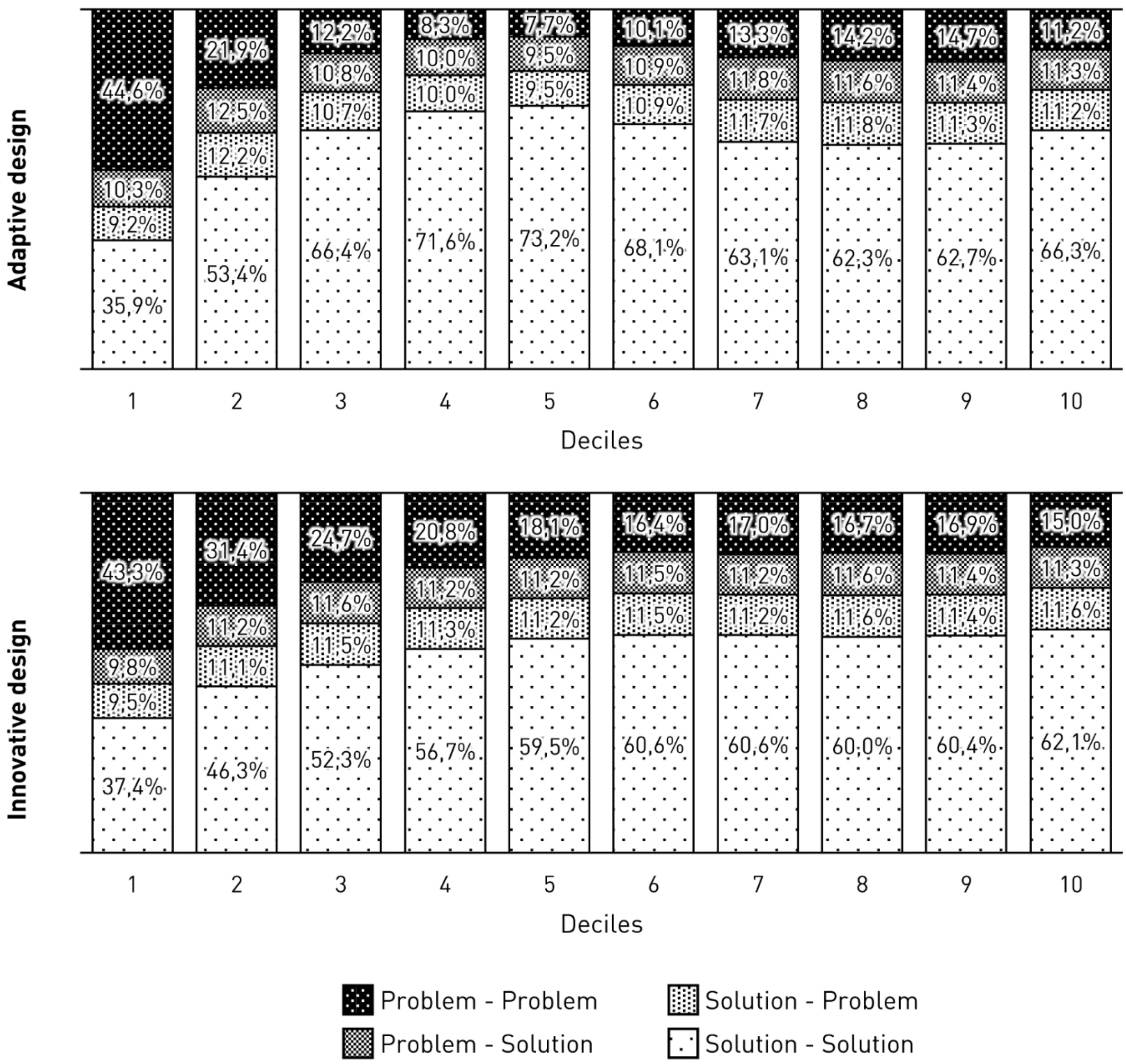

Figure 6.12 Average proportions of sequences of problem- and solution-related design operations across deciles of adaptive (top) and innovative (bottom) design simulations

Unlike in the adaptive design process, the average proportions of problem-related design operations decrease continuously until the end of the process (Figure 6.12, bottom). Interestingly, the average proportions of moves between the problem and the solution space do not change significantly with the progress of innovative design process. This means that sequences of several consecutive design operations within the problem space are more likely in the first deciles, whereas later in the process teams quickly switch back to the solution space. A similar claim can also be made for the adaptive design process.

7. DISCUSSION AND VALIDATION

The sixth chapter discusses the results and compares them to the insights available in the design research literature. The primary aim of this discussion and validation is to address the research questions using the findings obtained from the protocol analysis and computational studies. The extent to which the research questions have been clarified and compatibility with the existing research is thus used to validate the developed theoretical framework, the theoretical and mathematical models, and the associated visualisations.

As the final research step, the state-transition approach to modelling team design activity, which has been framed in the form of a theoretical model (Chapter 3), formalised in the form of a mathematical model (Chapter 5), and experimentally tested within protocol analysis (Chapter 4) and computational studies (Chapter 6), is discussed and validated in this chapter. The discussion has been structured in five sections, each of which addresses one of the research questions raised at the end of the research background chapter.

First, a reflection on the models and their ability to capture ASE and their interaction in team design activities (RQ1) is discussed in Section 7.1. Following is the discussion and validation of general state-transition patterns found in team conceptual design activity (RQ2) in Section 7.2. The discussion then focuses on patterns specific to the team ideation and concept review activities (RQ3) in Section 7.3, and the adaptive and innovative design in the conceptual design stage of technical systems development (RQ4) in Section 7.4. Finally, the overall trends identified for the progress of the conceptual design stage (RQ5) are discussed in Section 7.5.

7.1. Reflection on the state-transition model

The first point of the discussion addresses the research question RQ1, which prompted conceptualisation of ASE as information processing mechanisms performed by designers to manipulate the design information content in the problem and the solution space. This research question has initially been addressed within the theoretical framework chapter (Chapter 3), where the state-transition model has been proposed as a response. Following is a brief reflection on the utility of the model, based on the insights obtained from the protocol analysis and computational studies.

The benefit of adapting the definitions of ASE design operations built into the theoretical state-transition model manifests mainly in the proportions of solution analysis, problem synthesis and problem evaluation design operations. Firstly, the literature review revealed that analysis is often conceptualised only as a problem-clarification step in the design process (e.g. [75], [159], [195], [206]). However, the observed high proportions of solution analysis design operation (Subsection 4.3.1) reveal that teams spent a considerable portion of conceptual design activity increasing the understanding of design solutions. The theoretical model, therefore, exhibits the critical role of analysis as a design operation performed in both the problem and the solution space. For that reason, it can be argued that both problem and solution analysis should be traced as independent fine-grain steps in the conceptual design process, where the individual and shared understanding are increased by means of questioning and clarification, rather than being incorporated as part of the evaluation step (see, e.g. [203], [206]).

Secondly, the reviewed fine-grain models of designing articulate mainly the synthesis of new solution entities during the design activity (e.g. [54], [196]). Nevertheless, the observed high proportions of problem synthesis design operation (Subsection 4.3.1), especially during ideation, indicate that new problem entities are also appearing repeatedly throughout the team conceptual design activity. For example, ideation activities have shown highly probable cycles of problem synthesis design operations. Hence, by capturing the synthesis of design entities in both dimensions of the design space, the proposed theoretical framework complements the existing descriptive research efforts.

Finally, although neglected in some models of the design process, the problem evaluation design operation accounted on average for about 6% of all design operations during ideation, and 2% during concept review activity of the protocol analysis study (Subsection 4.3.1). In the computational study, problem evaluation exhibited average proportions of about 7% in adaptive design simulation and about 8% in innovative design simulations (Subsection 6.3.1). While these are relatively small proportions, they show that teams evaluate not only the proposed solutions but also the design entities within the problem space (e.g. requirement prioritisation and constraint assessment).

The theoretical model's ability to capture sequences of any pair of observable design operations (including the repeating cycles of a single design operation) has resulted in representations of the team conceptual design activity which could not be replicated by other descriptive models of designing. Particularly, many of the observed patterns during ideation and concept related activity (e.g. alternation of analysis and synthesis, and the repetitive cycles of synthesis or analysis) cannot be mapped directly on the reviewed design models. For example, the synthesis operation in the FBS framework can be followed by an analysis [26]. However, according to the FBS ontology coding scheme [192], synthesis can follow analysis only if evaluation appears in-between them. And while such transitions might be the case at a cognitive design level or for individual designing, the reported study showed that there are many observable episodes of analysis-synthesis moves appearing during team ideation and concept review. The same can be argued for synthesis-synthesis sequences occurring during ideation, and analysis-analysis and synthesis-evaluation sequences occurring during concept review.

Moreover, not all of the observed ASE patterns can be identically mapped onto the model of thinking in design teams by Stempfle and Badke-Schaub [54]. In their two-process model, new solutions must be followed by analysis or evaluation, and analysis must be followed by evaluation. Such constraints within the model prevent mapping of the aforementioned cycles. Again, this might be appropriate for modelling the thinking processes during the design process, but it does not reflect the nature of teams' observable design operations, which have a direct effect on the state of the product being design and the state of the design process. The IMoD [203] by Srinivasan and Chakrabarti is more flexible in terms of design operation sequences and provides a more detailed insight into design synthesis by dividing it into generation and modification. However, IMoD does not distinguish analysis from evaluation, although analysis has here been portrayed as an important and often used design operation.

The probabilities of sequences of ASE design operations mapped onto the state-transition visualisation reveal that, although the analysis-synthesis-evaluation sequence does appear in both during ideation and concept review activities, as well as in both innovative and adaptive design projects, the often-disputed model by Asimow [163] does not reflect the nature of conceptual design activity when using a fine-grain observational approach. The state-transition model has revealed that the analysis-synthesis-evaluation and synthesis-analysis-evaluation sequences are merely two of many appearing in team conceptual design activity.

7.2. Team conceptual design activity

The second research question RQ2 concerns the patterns of ASE altering inside and in-between the problem and the solution dimensions of design space, which can be observed during team conceptual design activities. Results of the various types of analyses reported in the protocol analysis study (Chapter 4) have been combined to address the question and discuss the alignment of new findings with the state-of-the-art insight available in the literature.

Although the proportions of segments related to discussions of problems versus solutions space alter across the four observed teams (problem-solution focus of teams can vary as shown by Jiang et al. [55]), there exist similarities in proportions of sequences of executing ASE design operations within these two dimensions of design space. This similarity can primarily be explored during ideation, where, according to Table 4.4, teams spent significantly more protocol segments discussing the problem space. Qualitatively, the average order of most likely moves between ASE design operations (Table 4.7) is consistent when considering sequences within the problem and sequences within the solution space. During ideation, synthesis is in both spaces most likely to be followed by analysis and least likely by evaluation. During concept review, in both of the spaces synthesis is also most likely to be followed by analysis and least likely by another synthesis design operation. Additionally, the most likely design operation to follow analysis during ideation was synthesis, and the least likely was analysis. On the other hand, the most likely move from evaluation during concept review was to analysis, again regardless of the dimension of the design space. These results can be related to the "find and modify" patterns of ideation, which Sarkar and Chakrabarti [210], [223] identified within both the problem and the solution space.

By analysing the sequential strings of coded segments for each of the observed teams, and the corresponding probabilities and proportions of moves between design operations, it is possible to examine the fine-grain patterns in teams' design processes. Figures 7.1, 7.2 and 7.3 utilise the state-transition model visualisation to illustrate three common patterns of ASE design operation sequences obtained for both the ideation and the concept review activity. These patterns are conceptualised as templates on which sequences of several design operations can be mapped to indicate common micro-scale building blocks of the team conceptual design process. The patterns were initially identified within the strings of protocol codes, as sequences of coded segments which are articulated due to their repetition. The identified patterns have then been further investigated by mapping the observed probabilities of moves between design operations reported in Table 4.7 and proportions of these particular sequences which have been presented in Tables 4.10 and 4.11.

The first pattern which is present in both activities (Figure 7.1) comprises the reciprocating cycles of solution synthesis frequently intercepted by solution analysis. Moves in-between solution synthesis and analysis have been shown as the most probable during both activities (Table 4.7). Moreover, adding up the proportions of state transitions reveals that 57.1% of sequences of two (Table 4.10), and 42.3% of sequences of three (Table 4.11) solution-related design operations during ideation can be mapped onto this pattern. As for concept review, the pattern includes 38.4% of sequences of two and 22.1% of three solution-related design operations. The first pattern can also be discerned in data simulated as part of the computational study (Chapter 6). It accounts on average for 42.8% sequences of two (Table 6.8) and 23.5% sequences of three solution-related design operations (Table 6.9) during adaptive design. The percentages of innovative design simulations covered by the first pattern are even higher: 52.1% of sequences of two and 34.9% of sequences of three solution-related design operations.

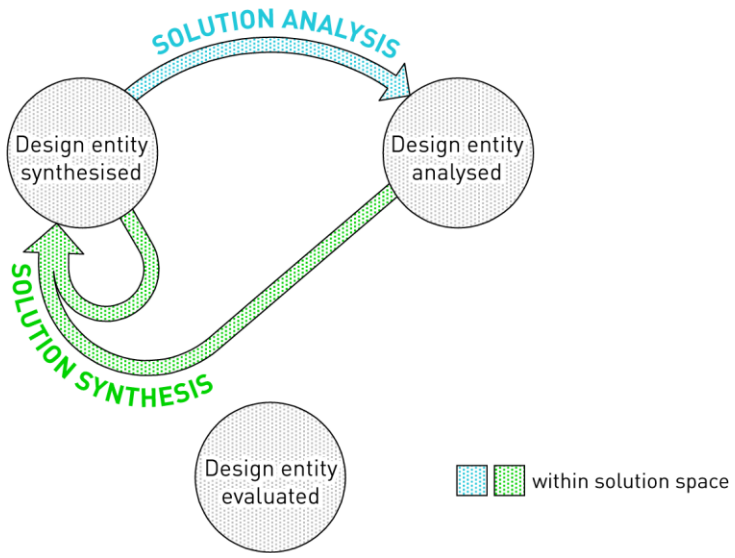

Figure 7.1 Cycles of solution synthesis and analysis

The cycles forming the first identified pattern have already been given attention in the literature. For example, Smith and Tjandra [259] interpreted analysis-synthesis cycles as iteration in design activity. They state that the iteration intensifies as conceptual design stage progresses. A similar interpretation has been provided by Sung and Kelley [189], who described the phenomenon as a bi-directional iteration of designing solutions and predicting possible consequences of the solution ideas. Cascini et al. [197] described the interplay of analysis and synthesis when moving from needs identification and requirements definition towards conceptual design stage. Furthermore, Sauder and Jin [56] have observed that questioning and clarification of design solutions (solution analysis) stimulates generative thinking processes which in return trigger generative (solution synthesis) design operations. Similarly, Cardoso et al. [188] interpreted questions as drivers of discourse in design team ideation activity. According to these studies, the analysis of the shared design space appears to be an important driver of stimulation responsible for the generative (synthesis) processes. Finally, the dominance of solution synthesis within the cycle can be characterised as a decoupled ideation [46], where solution ideas are appearing without the need of switching to problem space and triggering the co-evolution episodes.

The presented protocol analysis data thus support the claim that the alternation of synthesis and analysis in both the problem and the solution space is typical for conceptual design activities [158], [202]. An excerpt of the experiment session transcripts from the protocol analysis study, which demonstrates the first pattern, is available in Table 7.1.

Table 7.1 An excerpt of team discussion demonstrating the reciprocating cycles of solution synthesis and analysis

Participant	Segment transcript	Code
P1	[discussing attachment to the balloon] *We have to minimise the mass.*	PS
P2	*We could use welding.*	SS
P2	*Or... Uhm. Glue, adhesive.*	SS
P3 P2	*Adhesive? I guess we can call it both (glue and adhesive).* *Yes.*	SA
P3	*We also have Velcro.*	SS
P2	*You can put up magnetic.*	SS
P2	[gesturing] *Magnetic touch. I'm not sure how, but...*	SA
P3	*So, I guess we expand them now?*	PROC
P3 P2	*I got one actually, like a...* [gesturing] *I think is metal, like a flexible...* *Yeah, the Gorillapod thing.*	SS
P3 P2	*Is that what it's called?* *Yes. It's TP, thermoplastic.*	SA
	...	
P1 P2	[discussing which problem should be addressed next] *I think that camera movement is most important.* *OK.*	PE
P2	*If we want to move the camera mount from the base, I can think of one which has two sets of drills, rotation axes.*	SS
P2 P1	[gesturing] *One in this direction, and the other one in this direction. I don't know if you understood what I wanted to say?* *Yes.*	SA
P1	*You could have it on a ball.*	SS
P2 P2	*Oh, and then manipulate the ball?* *Yes, like a gyroscope or something.*	SA
P2 P1	*Can you sketch it?* [laughs] *Not really.*	PROC
P3	*Maybe driven by gears to control the angle.*	SS
P1	*You could have it... It does not have to be absolute any angle, because you could have like* [gestures] *30 degrees – 30 degrees – 30 degrees.*	SS
P3 P1	*Oh, distinct angles. Not continuous.* *Yes, distinct angles.*	SA

The second pattern of design operations (Figure 7.2) identified within both activities includes sequences of solution synthesis, analysis and evaluation. This pattern builds on the first (divergent) pattern by incorporating solution evaluation as a converging operation. According to protocol analysis study data (Tables 4.10 and 4.11), the summed-up proportions of state transitions included within the pattern account for 86.8% sequences of two, and 76.5% sequences of three solution-related design operations during ideation. Likewise, the pattern comprises 70.4% of sequences of two, and 51.1% sequences of three solution-related design operations during concept review activity.

In addition, the second pattern can reflect 76.5% of moves between two (Table 6.8) and 52.4% of moves between three consecutive solution-related design operations (Table 6.9) simulated for the adaptive conceptual design process, as well as 83.7% of moves between two, and 67.2% of moves between three consecutive solution-related design operations simulated for the innovative design process.

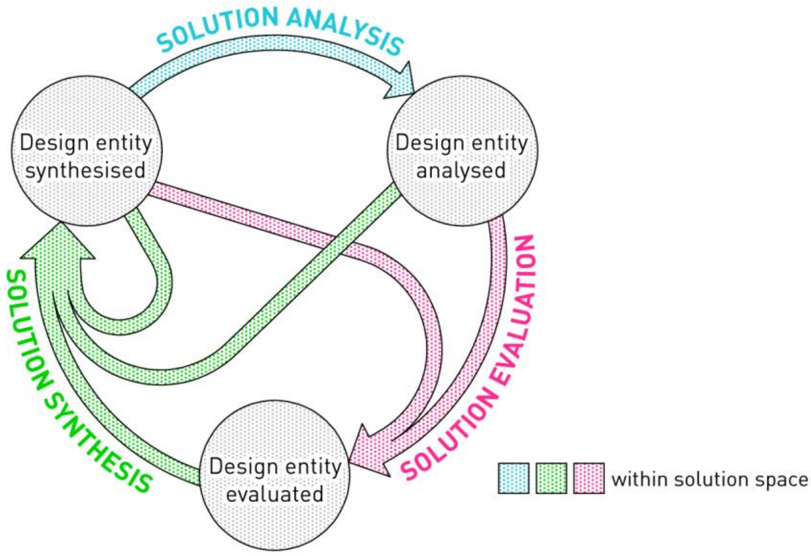

Figure 7.2 Sequences of solution synthesis, analysis and evaluation

The described sequences resemble the two types of thinking processes identified by Stempfle and Badke-Schaub [54], where synthesised solutions are either immediately evaluated (process 1), or first analysed and then evaluated (process 2). If the synthesised solution is discarded, a new idea will be sought [54]. A similar pattern can be described within the FBS framework, where a synthesised structure is first analysed to understand its behaviour, and then evaluated by comparing its behaviour to the expected behaviour [26]. An excerpt of the experiment session transcripts which demonstrates the second pattern is available in Table 7.2.

Table 7.2 An excerpt of team discussion demonstrating sequences of solution synthesis, analysis and evaluation

Participant	Segment transcript	Code
P1	[discussing alternatives to the universal screw camera attachment] *Duct tape – that is an idea.*	SS
P1	*I mean, it's not very usable, but...*	SE
P1	*We can use bands. Just bands.*	SS
P2	*Velcro?*	SS
P1	*Velcro. It can be sticked to the back of the camera.*	SA
P2	*Velcro works in space actually.*	
P3	*I think it works in space because there are no forces in vacuum.*	SE
P1	*But you could use it to connect... Like a pouch.*	SS
P3	*I'm not saying its a bad idea.*	SE
P3	*A bag? Bag / kangaroo pouch.* [laughs]	SS
P1	*The thing is, it's annoying if you have to screw your camera into something that is fixed, especially to a balloon...*	SE
P3	[interrupts and gestures] *A clip in.*	SS
P3	*Which can go* [points to written categories] *here?*	SA
P1	*Yes.*	

The third identified pattern (Figure 7.3) indicates co-evolution of the problem and the solution space by combining state transitions which result in switching in-between problems and solutions by means of synthesis design operation.

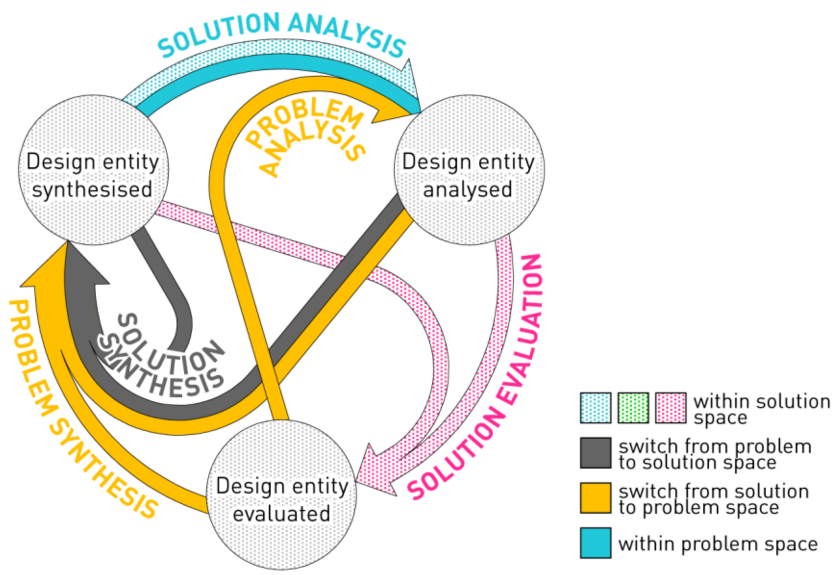

Figure 7.3 Synthesis as a means of switching in-between problem and solution space

State transitions which can be mapped onto the third pattern account for 56.6% of sequences of two (Table 4.10), and 30.8% of three consecutive design operations (Table 4.11) in-between the problem and the solution space during the observed ideation activity. If only sequences resulting in synthesis (as an indication of co-evolution) are considered, these percentages increase to 73.8% and 44.8%. As for concept review activity, 51.6% of sequences of any two, and 26.0% of any three consecutive design operations in-between the problem and the solution space can be mapped. Again, the percentages are higher (93.7% and 60.9%) if only transitions resulting in synthesis are considered.

In a similar manner, 38.5% of sequences of any two, and 22.5% of sequences of any three consecutive design operations simulated in-between the problem and solution space computational study of an adaptive process can be mapped onto the third common conceptual design pattern. These proportions increase to 77.1% for a sequence of two, and 25.2% for a sequence of three design operations, if only the switching of spaces that ends with a synthesis design operation is considered.

The results of innovative design simulations reveal that on average 52.9% of all sequences of two, and 26.5% of all sequences of three consecutive design operations that switch from problem to solution space or vice versa, can be mapped onto the third common pattern. If only sequences resulting in a synthesis of problem or solution entities are considered, the percentages increase to 80.0% and 27.1% respectively.

Once a synthesised solution entity is analysed or evaluated, a new problem is sometimes immediately discovered (synthesised) by the team members. As soon as the team develops a shared understanding of the new problem, they propose (synthesise) new solutions to the problem. In such co-evolution episode, the teams switch from solution to problem space and return to solution space. The new solution entity can again be further analysed and evaluated which can result in the identification of new problems. Such a pattern can be classified as a necessary part of refinement, a stereotype of progressive iteration as defined by Wynn and Eckert [157]. As the solution design goes through several levels of abstraction, each level can result in a new set of requirements [203], so the solution undergoes iterative refinement until evaluated as satisfying. The described iterative pattern also corresponds to what Cash and Štorga [46] define as integrated and iterative ideation since new solution ideas trigger new problems and vice versa. An excerpt of the experiment session transcripts which demonstrates the third pattern is available in Table 7.3.

Table 7.3 An excerpt of team discussion demonstrating synthesis as a means of switching in-between problem and solution space

Participant	Segment transcript	Code
P1	*I try to work out if we can get away with fewer motors than two.*	PS
P2	[points to previously discussed solution] *Exactly that's what I got over here.*	SE
P1	*Yeah. But I don't know, because if you wanted it pushing down and think 'Oh yes, I wanted that angle'. But it has only reached that far down and not…* [points to solution]	SA
P1	*Then you obviously can't use the exact rotation.*	SE
P1	*I think when you've got two degrees of freedom like that* [points to solution] *you need two… sort of… at least two motors.*	PS
P2	*What if you had a really tight spiral and it gradually taper it to a triangle?*	SS
P1	*Yes, so it's going through every conceivable thing just using one motor?*	SA
P2	*Yeah.*	
	…	
P1	*Could we just have like a… Plastic…* [starts sketching] *So it will be like that. And then we put it in. And then just have… It's like a plastic… Where you just push it, so it doesn't come out?*	SS
P2	*Yeah, like a clip.*	SA
P1	*Yeah, so instead of a locking mechanism. You can do it with one hand. Just push the latch and take it out, pull it out.*	
P1	*That would really simplify it.*	SE
P2	*I mean, my only concern with that is in case the latch came undone, because there's no spring holding it there. But in between somewhere of doing that [pointing to solution] and making sure it didn't come under…*	PS
P3	*What about a screw tightener thing… So that you have a notch inside…* [starts sketching] *You have your plate slit in, a little notch in the base thing. And you have a screw which just went in there.*	SS
P2	*So, it would be like a quarter inch screw and then just…* [gestures]	SA
P3	*Yeah.*	

7.3. Ideation and concept review

Following the identification of common patterns of ASE design operations within and in-between the problem and the solution space, the research question RQ3 prompted the recognition and analysis of patterns that differentiate ideation from concept review activity. The distribution of the coded design operations segments during the two types of experimentally studied conceptual design activities (Table 4.3 and Figure 4.4) and the corresponding t-tests (Tables 4.4 and 4.12) reveal that teams are likely to exhibit different proportions of ASE design operations when performing various types of conceptual design activities. The comparison of ideation and concept review has revealed that the proportion of all six coded design operations differs significantly for these two types of activities studied. Based on these findings, it is argued that the activity-specific probabilities of ASE design operations appearing within and in-between the problem and the solution space can be utilised to investigate and model the change in state of the product being designed and change in state of the design process as defined by Reymen et al. [183].

According to Table 4.4, teams exhibited significantly more problem-related discussion and solution synthesis during the ideation activity and significantly more solution analysis and evaluation during the concept review activity. Since ideation was the first collaborative activity of the teams, it was natural for them to seek a shared understanding of the problem [22], [58]. Moreover, the decrease of design operations in problem space (especially problem synthesis) can be related to the drop in new requirements appearing towards the end of the conceptual design stage, as identified by Chakrabarti et al. [260]. During the concept review activity, the teams were more familiar with the design problem (space). Such a trend is qualitatively aligned with the findings of Jiang et al. [55] and Gero et al. [192], which imply the decrease in the proportion of problem-related issues as the conceptual design progresses. Additionally, Gero and Jiang [191] conclude that the concept review activities seem to be more solution-focused than the designing (ideation) sessions.

Ideation is often characterised as a divergent activity, considering that the generative design operation (synthesis) dominates the convergent one (evaluation) [232]. The fact that synthesis was the most frequent design operation for all of the studied teams during ideation session favours such characterisation. Furthermore, the proportions of ASE design operations (Figure 4.4) correspond to the average proportions of the equivalent processes (within solution space) reported for the ideation activities in Gero et al. [192]. Their study suggests that these proportions are also affected by the type of ideation method used. For example, the protocol study of brainstorming sessions presented in Kan et al. (2011) shows a somewhat higher rate of synthesis design operation, mainly in the solution space. It can thus be argued that the application of design and creativity methods during the conceptual design activity will likely affect the fine-grain patterns of the design process.

On the other hand, the protocol analysis of the concept review activity has revealed significantly higher proportions of solution-related discussion, particularly manifested in higher proportions of solution analysis and evaluation design operations. The studies of conceptual design where the design brief instructed the proposal of a single concept solution (which had to converge) suggest that engineering design teams will most frequently perform solution analysis and solution evaluation design operations (solution analysis and problem clarification in Casakin and Badke-Schaub [261] and content analysis in Stempfle and Badke-Schaub [54], followed by solution evaluation). Moreover, despite the increase in solution-related discussion, the proportion of solution synthesis is significantly lower when compared to ideation, thus providing additional justification for describing concept review as mainly a convergent activity.

If the two activities are compared with the stereotypes of progressive iteration [157], a link can be found between ideation and exploration (divergence) stereotype, and between concept review and convergence stereotype. Wynn and Eckert [157] describe exploration as a concurrent and iterative initial development of the problem and the solution, where the ill-defined nature of design goals is emphasised. Such progressive iteration is reflected in the evolution and co-evolution of the problem space during ideation, as shown in Figure 7.4. Convergence is described as an iterative adjustment towards a satisfying goal, once the main form of the design has been determined at a certain level of definition [157]. During the concept review, the designers would select and synthesise the most promising concept and would then iteratively refine different aspects of the final solution proposal.

The comparison of the two activities has revealed not only the different proportions of design operations (Table 4.4) but also the activity-specific sequences of ASE design operations. The activity-specific sequences represent the moves between two design operations whose probability changed significantly between the two types of activities (Table 4.12). The sequences with significantly higher probabilities during ideation and concept review activities have been illustrated as state transitions in Figure 7.4.

The significant changes in the probabilities of design operation sequences identified in Table 4.12 and Figure 6.4 again point out the divergent features of the ideation and convergent features of the concept review activity. As described, the divergent alternation of solution synthesis and analysis (Figure 7.1) accounts for almost 60% of solution-related discussions during ideation. However, as shown in Figure 6.4, the divergent features of ideation are also reflected in higher proportions of synthesis moves within the problem space, but also in-between the problem and the solution space. On the other hand, convergent cycles during the concept review activity are characterised by the sequences of analysis and evaluation design operations performed as part of developing and refining the final proposal of the conceptual solution (Figure 7.2). As shown in Figure 7.4, the probability of evaluating a synthesised solution is significantly higher during concept review.

Furthermore, the evaluated solutions are more likely to be repeatedly analysed. Here, the analysis design operation is essential for the better understanding of team members, and leads to progress in team design activities, whether it is used as clarification [207], [261], or questioning [188]. And while teams can, in general, be seen as collective information processing entities, individuals within teams do not possess identical internal representations of problems and solutions [58]. Hence, achieving common ground (understanding), as highlighted by Hultén et al. [20], appears to be an essential ingredient of a team's creative process during conceptual design activities.

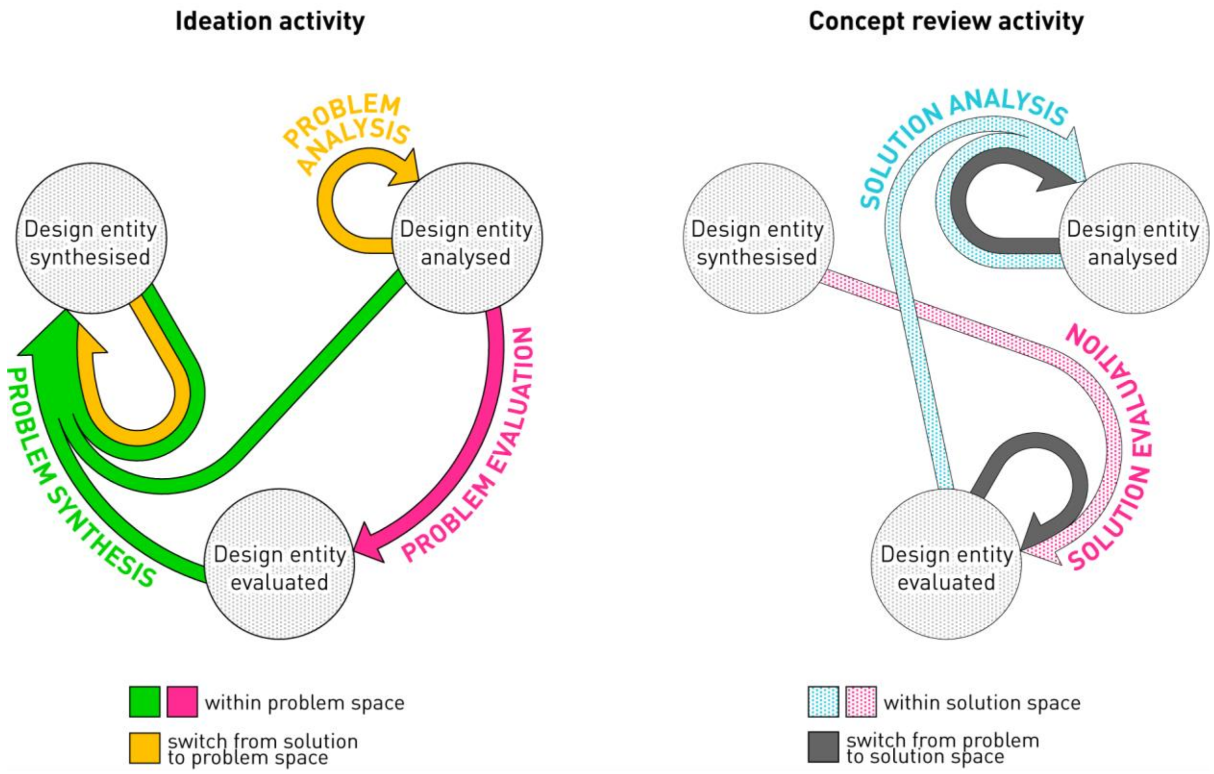

Figure 7.4 State transitions distinctive for ideation (left) and concept review activity (right)

Finally, the protocol analysis study provided an insight into teams' practices of using ASE design operations to switch from problem to solution space and vice-versa. An interesting finding is that moves from problem to solution space are performed mainly to synthesise new entities, while moves from solution to problem space appear either because a new problem was identified, or the focus is again set to the analysis of the existing problem entities. Such patterns support the concept of problem-solution co-evolution as described in studies by Dorst and Cross [161] and Visser [160]. Therefore, the moves in-between the problem and the solution space which result in the synthesis of design entities can be characterised as identifiers of the likely co-evolution episodes.

Although studies have reported co-evolution during both ideation and concept review activities (e.g. [215]), there have been no clear insights on how the rate of co-evolution changes with the progress of conceptual design activity. The protocol analysis shows moderately lower probabilities and frequencies of switching the space by performing synthesis design operation during the concept review activity, as opposed to ideation (moves from problem space to solution synthesis and from solution space to problem synthesis in Tables 4.7 and 4.10). Wiltschnig et al. [67] who analysed the phenomena of co-evolution during several conceptual design meetings have identified that most of the co-evolution episodes imply new solution entities, rather than new problem entities. Similar insights can be drawn in this study, since the moves from problem space to solution synthesis, which are characteristic for such co-evolution episodes have been more frequent than moves from solution space to problem synthesis, during both of the activity types (as shown in Table 4.10 and Figure 4.8). Nevertheless, while this was indeed the most likely space-switching scenario, the probabilities of space-switching moves which imply synthesis of problem entities (moves from solution space to problem synthesis in Table 4.7) must not be neglected, particularly during concept review. Namely, the convergent design activities are focused on evaluating solutions rather than creating new ones. The evaluation design operation has been defined in a way that it can implicitly reveal decomposed problems [158]. Such problem decomposition is argued to be the main reason why problem synthesis design operations are likely to follow solution evaluation if space is switched. Also, Wiltschnig et al. [67] reported that requirement analysis (problem analysis) is expected to trigger most of the co-evolution episodes, resulting in solution attempts (solution synthesis). The presented study shows that problem analysis certainly plays a valuable role in co-evolution during both ideation and concept review, expressed in the high probability of solution synthesis following problem analysis (Table 4.7). However, it was found that problem synthesis is more likely to be preceded by solution analysis and evaluation rather than solution synthesis when co-evolution occurs (as seen in Table 4.7 and Figure 7.3).

7.4. Conceptual design progress

The change in patterns of ASE design operations throughout the conceptual design stage can be approached in two ways. First, the results of the protocol analysis study (Chapter 4) can be used to compare the difference in two team activities at different points of the conceptual design stage (ideation at the beginning and concept review towards the end of the overall conceptual design process). Such a comparison has been presented and discussed in the previous section.

The other approach is to utilise the results from the simulation of conceptual design in adaptive and innovative design projects, reported as part of the computational study (Chapter 6). The commonalities found in the progress of the simulated processes of adaptive and innovative design can complement the protocol analysis study insights to develop an overall understanding of the relationship between the progress of conceptual design stage and patterns in performing design operations, thus addressing the research question RQ4.

Distinctive state transitions during ideation and concept review activities (Figure 7.4) revealed that the proportions and probabilities of moves within and towards the problem space are significantly higher in the earlier segments of the conceptual design stage. The decrease in problem-related segments has already been discussed as aligned with the findings of Jiang et al. [55] and Gero et al. [192]. In addition, a study of freshman and senior students' conceptual design process conducted by Altman et al. [262] revealed that the focus on problem scoping, that is problem definition and information gathering, has been most persisting from the beginning up until the end of the first half of the conceptual design stage. A similar pattern can be discerned in the protocols of Stempfle and Badke-Schaub [54], who analysed how teams execute a complete conceptual design task.

Nevertheless, since designers are "solution-led", rather than "problem-led", they tend to jump to solution ideas (or partial solutions) before they had fully formulated the problem [263]. For this reason, problem-related segments keep reappearing until the very end of the conceptual design stage. The constant development of problem space is best depicted by the average proportions of sequences of the problem- and solution-related design operations across the deciles of the conceptual design simulations (Figure 6.11) reported in Chapter 6.

The simulations of adaptive and innovative conceptual design (where problem-focus was one of the input parameters) indicated that, while the proportion of problem-related design operations decreases, the rate of switching between spaces does not change significantly throughout the conceptual design stage. What changes is that the simulated teams spent significantly fewer consecutive sequences within the problem space as the conceptual design stage progressed. It can be hypothesised that switching to the problem space later in the conceptual design process is related to discovering new problems or referring to the existing ones when evaluating concept solutions, rather than a deliberate exploration of the problem space. For example, Kan et al. [190] observed a decrease in the formulation and an increase in the reformulation of problem-related issues with the progress of a design session.

The results of the protocol analysis study indicate that when compared to the ideation activity, the concept review differs in higher proportions of solution analysis and evaluation, as well as higher probabilities of moves from solution analysis, synthesis and evaluation towards solution analysis, and from problem to solution analysis and problem to solution evaluation (Figure 4.8). The results of the computational study develop this insight further by depicting the increase in proportions of moves in-between analysis and evaluation (Figure 6.11) as adaptive and innovative conceptual design proceed.

Overall, it can be hypothesised that with the progression of the conceptual design stage, the initially higher proportions of synthesis cycles (divergent process) get gradually substituted by the alternation of analysis and evaluation design operations (convergent process). The divergent and convergent characteristics of the design process are thoroughly discussed in the previous section. Smith and Clarkson [264] explain that, while commitments made in the conceptual design stage are mainly functional, designers typically specify the realisation of the solution as they approach the latter stages of conceptual design. By developing the information how the design work, not only is the problem reduced, but it is also easier for the team to determine "what can go wrong" [264] and conduct solution evaluation. Fricke [265] argues that, as design problem formulations get more precise, the increase of solution evaluation is crucial for successful concept development.

Interestingly, the alternation of analysis and synthesis is fairly persistent throughout the protocols obtained from both the protocol analysis and the computational studies of conceptual design. This insight again points out the critical role of analysis-synthesis cycle for concept generation, as proposed by some studies [56], [188], [189], [198], [259], and discussed in the previous section. It can be argued that fractions of the design process where sequences of analysis and synthesis design operations alternate (the first common pattern discussed in Section 7.1) appear consistently throughout team conceptual design activities.

The discussion of the relationship between the patterns of design operations and the progress of the conceptual design stage can be concluded with a hypothesis that the drop of uncertainty (whether high uncertainty in the case of innovative design or medium uncertainty in case of adaptive design [44], [175]) is proportional to the decrease in proportions problem-related design operations, as well as inversely proportional to the increase of solution analysis and evaluation design operations. This hypothesis can be further investigated as part of future studies.

7.5. Innovative and adaptive design

The research question RQ5 is oriented at investigating the prevalent patterns of design operations which can be identified for different types of technical systems development. Here, in particular, the novelty aspect of the technical system has been selected as a type of engineering design. Two compared novelty levels were adaptive and innovative design. More details on the computational analysis of patterns of design operation within the adaptive and innovative conceptual design can be found in Chapter 6. The similarities between the two have already been analysed in the previous section, where the overall patterns that arise from conceptual design progress are discussed. This section focuses on the distinctive features of adaptive and innovative design processes simulated in Chapter 6 and demonstrates how these distinctive features can be identified using the proposed model. Three distinctive aspects are discussed hereafter: proportions of design operations sequences, co-evolution and systematic approach.

Based on the previous findings and due to a specific setup of parameters of the computational study (Section 6.2) it has been both expected and coveted that the adaptive design simulations inherit higher overall proportions of analysis, evaluation and solution-related design operations, while simulations of innovative design exhibit higher proportions of synthesis and problem-related design operations. What was unknown prior to the simulations was which types of patterns cause the overall proportions of design operations. The new insights thus do not arise from the average proportions of design operations, but the design operation sequences. For example, the analysis of sequence probabilities and proportions (Tables 6.7-6.9, Figure 6.9) can reveal the most evident differences between adaptive and innovative design projects, when it comes to approaching solution evaluation, solution synthesis or problem synthesis. Some of the distinctive patterns are shown in Figure 7.5.

In adaptive design, it was more likely and more frequent for the analysed and synthesised problems as well as analysed and synthesised solutions to be followed by solution evaluation when compared to innovative design. In addition, it was more frequent that solution analysis was preceded by problem and solution analysis, as well as solution synthesis and evaluation. On the other hand, solution evaluation is more likely to be followed by another solution evaluation design operations during innovative design. Analysis of three consecutive design operations reveals that both solution analysis and evaluation design operations frequently followed cycles of solution analysis during adaptive design and cycles of solution synthesis during innovative design. Innovative design is more likely to exhibit cycles of synthesis within the problem, the solution, as well as in-between the problem and the solution space. Moreover, new problem entities are more frequently immediately evaluated.

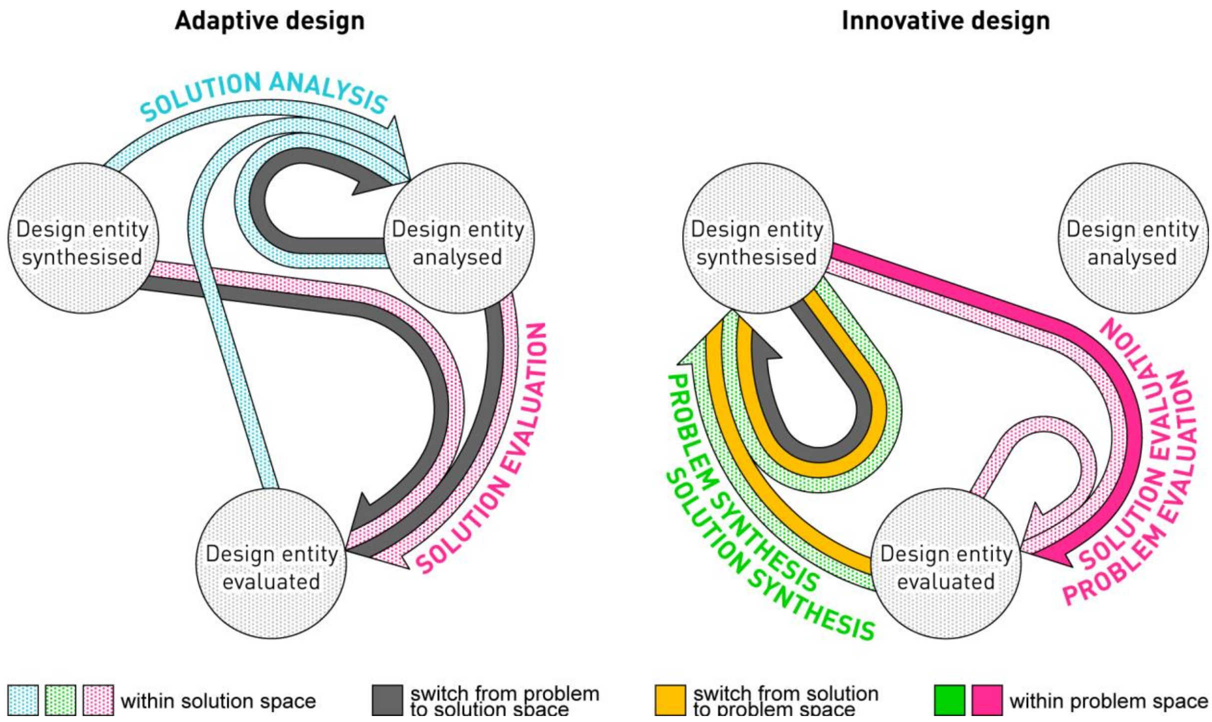

Figure 7.5 State transitions distinctive for adaptive (left) and innovative desing (right)

The above-listed findings for the adaptive simulations can be summarised as follows: whenever problem entities were synthesised, teams would frequently perform problem analysis to clarify the new problem or evaluate the existing solutions against the new problem; and often when solution entities were synthesised, teams would systematically analyse and evaluate the new entities. Innovative design is less, systematic and characterised by divergent sequences of problem and solution synthesis. Thus, when evaluated, the solution entities are likely to stimulate the synthesis of new problem entities. Such stimulation can be directly connected to the problem decomposition strategies observed by Liikkanen and Perttula [158]. In their model of problem decomposition, the more relevant knowledge the designers have, the more likely is that the problem decomposition will be explicit (e.g. in adaptive design teams deliberately analyse the problems at the beginning of the design process). Hence, in adaptive design, teams formulate problem at the beginning, and then systematically analyse and evaluation solutions against these problems. On the other hand, implicit decomposition appears throughout the innovative conceptual design, as solution synthesis and evaluation lead to the introduction of new problem entities. Based on the studies conducted by Guindon [266] and Purcell et al. [267], Atman et al. [262] argue that such “opportunistic decomposition” is more effective for ill-structured nature of design problems (as innovative designs are by definition). After all, Cross [263] argues that in the context of creative design, it is the evaluation of solutions that is important to designers, not the analysis of the problem.

Different approaches to problem and solution synthesis are also directly related to problem-solution co-evolution. Wiltschnig et al. [67] emphasise that co-evolution episodes are closely related to the epistemic uncertainty, that is when designers are unsure about how to proceed based on their current state of knowledge. For example, their study has shown that problem space exploration was more likely to arise within co-evolution episodes than outside and that designers were frequently trying to synthesise solutions following uncertain exploration of problem space [67]. It can thus be hypothesised that due to the high levels of uncertainty attributed to innovative design, it exhibits significantly more co-evolution episodes, manifested in cycles of continuous synthesis of solution entities, which in return stimulate the generation of new problem entities, either directly by following solution synthesis, or indirectly through solution evaluation.

The uncertainty may as well be related to a more systematic approach observed in adaptive design. Namely, while both the computational studies of adaptive and innovative design have been set up with distinctive five steps (each having significantly different proportions of ASE and problem- and solution-related design operations), the average proportions of design operations and their sequences across the deciles are more pronounced throughout the adaptive design process (Figures 6.9-6.12). More precisely, divergent and convergent features of conceptual design are more evident in the averaged results of the adaptive design simulations. The average adaptive design process exhibits higher proportions of the divergent synthesis design operation at the beginning of conceptual design, before noticeably switching to convergent sequences of analysis and evaluation. Fricke [265] calls this “balanced search”, where designers alternate between diverging and converging, whereby the global search space is noticeably reduced, and solutions become more concrete. Likewise, Tversky and Chou [268] relate divergent thinking to producing more unrelated themes, and convergent thinking to producing interrelated elaboration od the same theme. As long as an idea is not fully elaborated, it cannot be evaluated as feasible. Moreover, they highlight that in the context of creative (innovative) design, it is not always easy to know whether to think divergently or convergently [268]. According to Toh et al. [222], the ability to converge faster during adaptive design can, among other things, be related to the designer’s familiarity with the (technical system) design.

Namely, better familiarisation was found to cause earlier fixation, and thus result in "less innovative designs".

Interestingly, adaptive and innovative features can be also be assigned to methods and people. For example, López-Mesa and Thompson [269] explain that adaptive divergent methods generate solutions by successive incremental improvement or through new combinations of existing sub-solutions, whereas innovative divergent methods facilitate the search of novel solutions by breaking the paradigm or by abstract association. On the other hand, adaptive convergent methods evaluate precise, numerical data and innovative convergent methods evaluate approximate, soft data. Similarly, adaptors tend to develop solutions that are improvements, under low uncertainty, whereas innovators tend to work at a higher level of uncertainty and with novel and less matured solutions [269].

8. CONCLUSION

The final chapter reflects on the aims, the hypothesis and the expected contributions introduced within the first chapter. It reemphasises the core findings developed throughout the thesis and links them to the initial research expectations. In addition, this chapter discusses the main research limitations and provides suggestions for conducting further research related to information processing in teams developing technical systems.

The research reported in the thesis attempts to improve understanding of designing in teams, particularly in the stage of conceptual design and from the perspective of information processing and interaction. In order to achieve this, a more specific research aim has been formed as follows: to review, develop and test models of team design activity in the development of technical systems, which will build on information processing and interactions appearing in team design activities in the conceptual design stage of the development. The main purpose of these models is to enhance decision-making and planning of technical systems development, by enabling both capturing and generation of data sets that reflect patterns in the design process distinctive for specific team compositions and working processes. This concluding chapter decomposes the main research aim, summarises the key findings and outlines the main contributions to the research of team conceptual design activity.

Prior to any theoretical development, a comprehensive review of engineering design models has been conducted. The review enveloped models of different levels of granularity, from the overall NPD and engineering design process models as contextually relevant to the models individual and team design activity as a means of a fine-grain analysis of designing. The review formulated research gaps and research questions that directed the development and testing of the model. The focus has from here on been set to patterns of analysis, synthesis and evaluation as fundamental information processes used to manipulate design entities within the problem and the solution dimension of the design space, and how they change depending on the type of activity, novelty of product being designed and progress of the conceptual design stage. Hence, reporting on the research background (Chapter 2) achieved the aim of reviewing models of team design activity.

Two models have been developed as part of the prescriptive research stage. First, the theoretical model is formulated within the theoretical framework chapter (Chapter 3). The most relevant elements of the state-of-the-art models have been synthesised into within a single theoretical framework. Definitions of analysis, synthesis and evaluation as design operations within both the problem and the solution space have been formulated and incorporated into a state-transition model of team conceptual design activity. The theoretical framework also defines the key variables, measures and visualisation templates that encompass the model.

The developed theoretical model has been tested in the first experimental study (Chapter 4), where it was used as a means of capturing, identifying and visualising design operation patterns in two types of team conceptual design activity. The first experimental study was conducted in the form of a verbal protocol analysis study. The coding scheme and measures for the observable information-processing steps in the design process have been formulated to match the theoretical foundations. Proportions of design operations and proportions and probabilities of their sequences have been investigated for a total of four teams performing ideation and concept review activity. The state-transition model enabled identification of both activity-specific patterns of design operation proportions and sequences (e.g. divergent cycles of problem and solution synthesis during ideation activity and convergent cycles of solution analysis and evaluation during concept review), as well as patterns common for the conceptual design stage (e.g. cycles of solution analysis and synthesis, and synthesis as means of switching between the spaces). It has been confirmed that, as the conceptual design stage progresses, the number of problem-related design operations decreases. The presented analysis also revealed that design teams utilise similar sequences of ASE design operations as they progressively explore the problem and the solution space during ideation. Despite the relatively low proportion of problem-related discussion during concept review, it has been shown that design operations in problem space play an important role within the refinement and convergence cycles. Hence, the conceptualisation of ASE as design operations performed similarly in the problem and the solution space provided new insights which complement the research on the co-evolution of the two spaces. Given the iterative nature of designing and the ill-defined nature of design problems in the conceptual design stage, it is unsurprising that neither the observed ideation or the concept review activities followed the microscale cycles of analysis-synthesis-evaluation or synthesis-analysis-evaluation, as suggested by some of the reviewed models.

Insights from the protocol analysis study have been utilised for the second part of the prescriptive research stage, the development of a mathematical model (Chapter 5). The relationships between the variables of design operation proportions and sequences have been identified within the protocol analysis data, and regression analysis was used to formalise these relationships. The mathematical model was developed by combining the regression equations and the theoretical assumptions proposed in Chapter 3. Before being applied in a second experimental study, the predictive power of the mathematical model has been tested by simulating the results of the protocol analysis study.

After a satisfactory replication of the protocol analysis study results, the mathematical model has been utilised as a means of simulating proportions and sequences of design operations, based on a predefined setup of team conceptual design process (Chapter 6). An Excel-based computational tool has been developed for this purpose, and a test-case computational study has been conducted to compare the conceptual design stage of adaptive and innovative design projects. While the difference in steps and proportions of design operations were expected due to the experiment setup, the analysis of sequences of design operations has revealed some additional insights. For example, the two simulation setups resulted in different patterns of sequences following the newly synthesised solution and problem entities, where the innovative design exhibited features that resemble the co-evolution process. On the other hand, the interplay between ASE and the cycles of two design operations throughout the conceptual design indicate that adaptive design follows a more systematic approach.

Finally, the discussion and validation chapter (Chapter 7) discusses the experimental results and the extent to which the purpose of the developed models has been met. The model has been tested both as a support for gathering and structuring data about team information processing and as a support for generating such data under new initial conditions. Specific working processes included two distinctive conceptual design activities (ideation and concept review), and two distinctive novelty levels of the technical system being developed (adaptive and innovative design). Specific team compositions have not been investigated; however, it is here argued that the same approach could be utilised for such efforts.

From the design research perspective, it can be concluded that the scientific contribution is manifested in providing a valid description of team design activity and utilising the developed description in order to improve the understanding of team designing. Three main aspects of contribution can be outlined.

The first aspect of contribution concerns the state-transition theoretical framework and the accompanying theoretical model. It is argued that the developed state-transition model has fulfilled the purpose of supporting design research activity. The results of the protocol analysis and computational studies indicate that the theoretical model can be used to identify and analyse design process patterns such as sequences of design operations which are distinctive for specific working processes (e.g. divergent and convergent team conceptual design activities), as well as for a systematic approach to conceptual design. The experimental findings which could have been compared to the insights from the design research literature have been found aligned with the current understanding of designing in teams. The main advantage of the proposed theoretical model is its ability to map various sequences of ASE design operations which emerge during team design activity. Based on the listed findings, it can be argued that the developed theoretical model provides more flexibility when it comes to capturing and comparing the patterns of ASE design operations in the problem and the solution space and offers the potential of improving the understanding of the design process through either protocol analysis or computational studies of team conceptual design activity.

The second aspect of contribution concerns the mathematical model and the accompanying computational tool. It has been shown that if given the moving-average proportions of three input parameters, the mathematical model can satisfactorily replicate proportions and sequences of design operations observed in the protocol analysis study. Moreover, the algorithm developed as part of extending the mathematical model into a computational simulation tool includes the concepts of iteration and uncertainty in order to distort progress predefined by the systematic process steps. The test-case computational study has demonstrated the applicability of the mathematical model can be used as a means of simulating differently set up stages and activities within the engineering design process.

Finally, the third aspect of contribution concerns the proposed visualisation of state-transitions. It is argued that the visualisations augment the understanding of design operation patterns emerging during team conceptual design activities in two ways. First, as a summary of moves between ASE design operations within and in-between the problem and the solution space, where line thickness and colour coding are utilised to depict the frequency and types of transitions between the states of the explored design space. Second, as a template for mapping and visualising both the common and the activity-specific patterns of design operation sequences that can be identified during team conceptual designing. In addition, it is argued that the triangular visualisation of process steps based on the moving average proportions of ASE design operations enables intuitive analysis, comparison and characterisation of processes performed by different teams. It can be used for both describing and investigating phenomena such as iteration, uncertainty, exploration and systematic approach to design.

Prior to reviewing, developing and testing the models, it was hypothesised that the modelling and simulation of information processing and interactions of individuals that perform teamwork activities, enables understanding of the features of innovative and adaptive technical systems development and thus facilitate research, planning and management of development projects. As discussed above, understanding has been improved not only for the features of innovative and adaptive technical systems development but also for ideation and concept review activities and teamwork throughout the conceptual design stage in general. Better understanding derived from the obtained insights, together with the potential of simulating new ones, can help researchers and project managers in developing and prescribing the most appropriate and efficient methods and tools for the particular design tasks. However, the potential of enhancing decision-making in planning and management is yet to be further explored. At this point, additional research must be conducted to ensure that the models are robust, reliable and validated and that the designed support tool is easy to implement in design and project management practice. Guided by the recommendation found within the DRM methodology [30], the presented results are instead seen as part of a sound foundation for the effective and efficient realisation of tool development and potential implementation of research results into engineering design practice.

8.1. Research limitations

Research limitations are primarily related to the quantity and quality of data collected through the protocol analysis study and analysed via the computational study. Although statistically significant differences have been identified between two types of team conceptual design activities, larger sample sizes are preferable in future studies to validate the hypothesised claims and patterns. Using larger sample sizes and performing protocol analysis studies of adaptive and innovative projects would also result in more precise regression models and better predictive power of the computational simulation tool. In addition, due to the scope of the dissertation and space available, only a single test-case computational study has been reported. Additional studies are required to build data sets sufficient for further in-depth analyses of team design activity. For the computational tool to be entirely useful as a means of approximating the design process, the simulator must be fully verified, validated and calibrated, particularly in terms of its implementation, accuracy and precision.

The presented research has examined only the distribution and sequences of ASE design operations, without investigating the rationale for the transitions inside and in-between the problem and the solution space. Experimental studies focused strictly on the reasoning for particular design operations could provide a further understanding of the patterns identified during the team conceptual design activities.

An additional limitation has been recognised in the lack of describing the context of team discussions. The derived patterns are based solely on the strings of design operations codes. For instance, when capturing a sequence of solution analysis following solution synthesis, it was not examined if the two design operations involve the same design entity. The context is also directly related to understanding iteration, that is, when and how iteration appears during team design activities. Hence, in the future, the additional dimension of discussion context could help in both capturing and simulating patterns of ASE design operations related to a single or a group of related design entities in the problem and the solution space. For example, IMoD [203] utilises three dimensions to link the process, the design spaces and the outcomes, thus enabling the tracking of activity patterns related to individual design entities. Moreover, the Linkography method [28], [232] can also be used to mark segments of activity which are associated with the evolution of a single design entity.

Similarly, the study is limited in addressing design operations solely on the team level. Hence, the protocol data does not provide information on team members which took part in the sequences of design operations. Another issue which has not been investigated is the relation between the roles of individual team members and their contribution to performing design operations. It is suggested that further studies include an additional layer to the coding process, which would provide data on who is taking a turn.

Finally, interactions encompassed by the model include only the interplay between design operations. Although they might have a significant effect on the investigated aspects of the design process, the interactions of team members, such as turn-taking or verbal engagement [270] have not been considered. Capturing the interaction of team members would add a layer of information to the protocols, which can be coupled with the analysis of proportions and sequences of design operations to provide a richer picture of team designing.

8.2. Future work

Besides the additional work required to address the research limitations, there also exist several possible directions for further developments and research extensions. For example, the proposed state-transition model can be used to investigate the effects of design methods, environments and team members' characteristics (background, experience, motivation, personality, problem-solving style, etc.) on the patterns of ASE design operations performed in the problem and the solution space. Earlier studies have shown that the methods used during team design activities [192], designers' background [55], [191] and the type of communication (virtual vs face-to-face) [27] can affect the team's design process.

Future work might also investigate the applicability of the model to describe team activities in different stages of the design process. In the presented study the focus was set on conceptual design activities since the conceptual design stage has been regarded as critical for the co-development of the problem and the solution space. Nonetheless, it is argued that team activities in the stages of planning, embodiment or detailed design could also be investigated using the proposed state-transition model.

Besides the design novelty levels, different engineering design projects are likely to encompass tasks of varying degrees of complexity, include teams of different sizes and team members of different expertise. These dimensions are likely to alter patterns of performing design operations at a different point within the development process. Future studies should utilise state-transition modelling to comprehensively investigate the effects that these dimensions have on information processing and interactions between team members.

Finally, the rationale for the probabilities of specific transitions (design operations) between the states could be hypothesised and investigated. For example, synthesis of a new design entity might be studied as a result of association, transformation or memory-based thinking processes of designers [56], [232]. Similarly, analysis as a result of questioning and misunderstanding [54], [56], and evaluation resulting from the need for narrowing the design space (see, e.g. the research studies conducted by McComb et al. [271], and Yilmaz and Daly [231]) can be investigated in the future.

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BIOGRAPHY

Tomislav Martinec was born in Čakovec, Croatia, in 1989. After graduating from gymnasium, he enrolled in the study of Mechanical Engineering at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb (UNIZAG-FSB) in 2008. In 2012, he gained a bachelor's degree and a year later a master's degree in mechanical engineering, specialising in Product Design and Development. During his studies, he was awarded the "Davorin Bazjanac Award" and the "Faculty Medal".

After graduation, he accepted the Teaching Assistant position at the Chair of Design and Product Development at UNIZAG-FSB. His primary field of research and scientific focus in the last years includes information traceability and visualisation in product development, management of relations between engineering objects and teamwork in the conceptual design stage. He has co-authored 3 journal papers and 12 conference papers.

He currently participates in Croatian Science Foundation (CSF) project "Team Adaptability for Innovation-Oriented Product Development – TAIDE". From 2014 to 2018 he was part of a CSF project "Models and Methods of Innovation Management in Complex Engineering Systems Development – MInMED". From 2015 to 2017 he participated in Erasmus+ project "Networked Activities for Realisation of Innovative Products – NARIP".

He visited Luleå Technical University several times throughout his doctoral research. In addition, he enrolled in summer schools organised by the Technical University of Denmark, Otto von Guericke University in Magdeburg and University of Malta.

He is a member of the Design Society. Since 2014 he actively participates in the organisation of the DESIGN conference, a biennial event that regularly attracts more than 250 experts from more than 30 countries around the world.

ŽIVOTOPIS

Tomislav Martinec je rođen u Čakovcu 1989. godine. Po završetku Prve gimnazije u Varaždinu 2008. godine upisuje Studij strojarstva na Fakultetu strojarstva i brodogradnje, Sveučilišta u Zagrebu (UNIZAG-FSB). Diplomu prvostupnika inženjerstva strojarstva stekao je 2012. godine, a godinu dana kasnije stekao je zvanje magistra inženjera strojarstva na usmjerenju Konstruiranje i razvoj proizvoda. Za vrijeme studija nagrađen je priznanjima "Davorin Bazjanac" i "Medalja Fakulteta".

Od 2014. godine zaposlen je kao asistent na Katedri za konstruiranje i razvoj proizvoda. Primarna područja istraživanja proteklih godina uključuju sljedivost i vizualizaciju informacija u razvoju proizvoda, upravljanje relacijama između inženjerskih objekata, te timski rad u fazi koncipiranja proizvoda. Koautor je 3 rada u časopisu i 12 radova na međunarodnim konferencijama.

Sudjeluje kao suradnik na projektu Hrvatske zaklade za znanost pod nazivom "Timska adaptabilnost u razvoju inovativnih proizvoda – TAIDE". Od 2014. do 2018. godine sudjelovao je na HRZZ projektu "Modeli i metode upravljanja inovacijama u razvoju kompleksnih inženjerskih sustava – MInMED". Od 2015. do 2017. godine sudjelovao je na Erasmus+ projektu "Networked Activities for Realisation of Innovative Products – NARIP".

Tijekom istraživanja nekoliko puta je boravio na Tehničkom sveučilištu Luleå, te sudjelovao na međunarodnim ljetnim školama u organizaciji Danskog tehničkog sveučilišta, Sveučilišta Otto von Guericke u Magdeburgu te Sveučilišta na Malti.

Član je zajednice Design Society. Od 2014. godine aktivno sudjeluje u organizaciji međunarodne DESIGN konferencije, koja svake dvije godine privlači više od 350 stručnjaka iz više od 30 zemalja iz cijelog svijeta.

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