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Applications of Axiomatic Design in academic publications 2013-2018

A Systematic Literature Review

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TIIVISTELMÄ:
Aksiomaattinen suunnitteluteoria on ollut kasvavan kiinnostuksen kohteena tiedeyhteisössä siitä lähtien, kun Nam P. Suh esitteli teorian 1990-luvulla. Siitä huolimatta, että aiheesta on tehty runsaasti aktiivista tutkimusta (muun muassa vuotuinen aksiomaattiseen suunnitteluteoriaan keskittynyt konferenssi), kattavia kirjallisuuskatsauksia on kirjoitettu vähän. Tämä tutkimus pyrkii osaltaan täyttämään edelläkuvattua aukkoa aksiomaattisen suunnitteluteorian tutkimuskentällä, keskittyen julkaisuihin vuodesta 2013 vuoteen 2018. Tutkimus on kirjoitettu jatkumoksi vuonna 2010 tutkijoiden Kulak, Cebi & Kahmaran (2010) julkaisemalle kirjallisuuskatsakuselle. Tämän vuoksi samankaltainen kategorisointi on implementoitu tähän tutkimukseen. Kategorisoinnin perusteina ovat käytetty aksiooma, sovellutusalue, metodologia ja määrittelytyyppi. Sovellutusalueisiin on tässä tutkimuksessa lisätty ’palvelut’ omana, uutena kategorianaan. Työssä esitellään lyhyesti aksiomaattinen suunnitteluteoria ja sen keskeiset osa-alueet, tärkeimpinä sunnnittelualueet, suunnitteluprosessi ja suunnitteluaksioomat. Metodologia-osiossa taustoitetaan systemaattisen kirjallisuuskatsauksen soveltamista tähän tutkimukseen ja kuvataan prosessin toteutus PRISMA-mallia käyttäen. Tutkimustulokset käydään lyhyesti läpi esimerkein kustakin kategoriasta. Tutkimusaineisto esitetään sekä lukuina, liitteenä että graaffeina. Näitä kirjallisuuskatsauksen tutkimustuloksia verrataan varhemman tutkimuksen vastaaviin. Sovelletun aksiooman suhteen merkittäviä muutoksia ei ole havaittavissa tämän tutkimuksen perusteella aikaisempaan kirjallisuuskatsaukseen verrattuna. Sovellutusaluessa, sitä vastoin, systeemisuunnittelun osuus on kasvanut merkittävästi edelliseen tutkimukseen verrattuna, kun taas ohjelmistosuunnittelun osuus on vastaavasti pienentynyt. Palvelusuunnittelun osuus on verrattain vaatimaton, joskin suurempi kuin esimerkiksi ohjelmistosuunnittelun. Tämän tutkimuksen perusteella suositellaan jatkotutkimuksia erityisesti aksiomaattisen suunitteluteorian sovellutuksista ohjelmisto- ja palvelusuunnitteluihin sekä mahdollisista syistä, miksi mainittujen sovellutusaljen osuus tutkimuskentässä on pienehkö.

AVAINSANAT: Axiomatic Design, Axiomatic Design Theory, Information Axiom, Independence Axiom, Systematic Literature Review, SLR, AD

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Abbreviations

AD	Axiomatic Design
SLR	Systematic Literature Review
CA	Customer Attributes
FR	Functional Requirement
DP	Design Parameter
PV	Process Variable
LT	Lower Triangular (matrix)
UT	Upper Triangular (matrix)
TFN	Trapezoidal / triangular fuzzy numbers
CPD	Collaborative Product Development
FAD	Fuzzy Axiomatic Design
TRIZ	Theory of the resolution of invention-related tasks
AHD	Analytic Hierarchy Process
QFD	Quality Function Deployment
FINNA	University of Vaasa article database
RQ	Research Question
REA2CT	Robust Enterprise-based Approach to Agility in Capability Trough-life
ICAD	International Conference of Axiomatic Design
RCT	Randomized Control Trials
ARD	Analytic Robust Design

1 Introduction

Axiomatic Design, shortened as AD, has gained a significant interest especially for early phases of design since launched by Nam P Suh in 1990s (Morrison & All 2013: 712). There is a large number of papers and researches published among the subject, for different applications. Furthermore, an international conference of Axiomatic Design has been ongoing since 2000 where researchers interested on the topic can gather together around AD in general and especially around papers selected on conference of the particular year (World Academy of Science, Engineering and Technology 2020). Despite active research around the topic of Axiomatic Design, very little secondary research, a research of researches aka Systematic Literature Reviews of the subject has been carried out.

Because of limited amount of secondary research such as Systematic Literature Reviews of Axiomatic Design, during the process of seeking possible subject for major thesis it was suggested by professor at University of Vaasa, that since this kind of research of the specific theory of AD is very limited, it would be not only interesting but also useful topic to explore. As well, methodology as a Systematic Literature Review was suggested since there is no particular study that is covering this methodology of publications of AD theory. However, as further explained below, there is previous study using a methodology that could reasonably be evaluated as a Systematic Literature Review even though the term is not used in that paper.

Kulak, Cebi & Kahraman (2010) published a paper with title “Applications of axiomatic design principles: A literature review” where authors review publications of Axiomatic Design from 1990 till 2009. A need for research was recognized since, as authors summarize, “there is lack of comprehensive literature survey which evaluates and classifies these papers [of Axiomatic Design]” (Kulak, Cebi & Kahraman 2010:6705). Authors decided to use four types of classifications for published papers in their research

dividing them according to used axiom, evaluation type, application area and theoretical contents (Kulak, Cebi & Kahraman 2010:6705).

However, since comprehensive literature review of Kulak & all, no complementary study of more resent publications of Axiomatic Design have been done. On the other words, since 2010, there is a gap of research regarding on publications of Axiomatic Design regarding on how theory has been applied as per previous categorization. Based on this gap and hereby need of research, a systematic literature review of publications regarding to Axiomatic Design is decided to carry out as a subject of Master's Thesis. Since there is a possibility to compare and contrast results with previous study, an interesting view of thesis is to find out whether there is a significant change on share of publications based on classification. Thereby, research questions are formed as following:

> RQ1: Has there been a significant change in application of Axiomatic Design in past five years compared to the literature review by Kulak, Cebi & Kahraman (2010)?

Since this question is quite open and depends on what part of previous study is compared with findings of thesis, research question RQ1 is further decomposed into following questions to enable more structured comparison:

> RQ1.1 Has there been change in proportion in use of information / independence axioms?
>
> RQ1.2 Has there been significant change of applications of Axiomatic Design?

Furthermore, to present findings from a new perspective, one that is among interests of the author, a share of applications regarding designing of services was added as a third element of research question as per following:

> RQ1.3: What is proportion of services in applications of Axiomatic Design within research range?

Based on theory of Axiomatic Design as presented in chapter 2 and on the aspect of research questions, classification defined in previous study is appropriate in context of Axiomatic Design and is therefore applied for present research as well to ensure comparison and contrasting. In a sub-classification criteria, some minor changes were decided for present research to support research question RQ1.3. In application area – sub-classification criteria were added “services” to separate applications of AD applied for service design from e.g. product and software system designs.

Furthermore, some limitations and a new gap for research was caused when exploring inclusive-exclusive criteria as explained in chapter 3 – Methodology. Since number of publications concerning Axiomatic Design was significant, limitations based on publications year had to be made. A six-year range was decided to be carried out for most recent studies at the time when research started, in December 2018. Thereby, publications published between 2013-2018 were selected as a part of this research. On the other words, there remains a gap between previous study which ended in 2009 and this research that presents articles published between 2013-2018. If such a study is to be carried out, and also if more recent articles from 2019- are to be researched, a conclusive study from all presented literature reviews could be beneficial to execute.

2 Axiomatic Design

In this chapter, a brief and concluded explanation of background and concept of Axiomatic Design (AD) theory will be delivered. Presumably this will present a basic knowledge of AD theory for reader who presumably has none. This is to understand Systematic Literature Review (SLR) and certain concepts selected for this study such as categorization and benchmarking study. Said Systematic Literature Review is explored in chapters 3-5 and concluded in chapter 6.

2.1 Background

Axiomatic design theory was established by Nam P. Suh in 1990s and furthermore explored specifically in his books "AXIOMATIC DESIGN Advances and Applications" published in 2001 and "COMPLEXITY" which was published in 2005 (Kulak, Cebi & Kahraman 2010: 6705). An awareness of significance of good design had already been arisen by when Suh introduced AD. This was not necessarily due to customers who were demanding better and better design straight-forwardly from companies, but because more and more companies noticed how costly bad design was (Helander & Lin 2002: 321). As Suh concludes in "AXIOMATIC DESIGN Advances and Applications" (2001: 2), all bad designs can "be dangerous, cost money, limit usefulness of product or delay introduction of products".

Axiomatic design was introduced by Suh to provide scientific framework for design, to form a theoretical foundation, logical process and tools to design (Cebi & Kahraman 2008: 411). Hence, AD was established to provide answers needed to solve problems of poor design. According to authors (Suh 2001: 3; Cebi & Kahraman 2008: 412), design is an interrelationship between *what* we want to achieve and *how* that is to be achieved. This also means that to be able to provide a good design or to success in design, one must first form design goals in terms of what we want to achieve (Suh 2001: 3). In other words, if this part of design fails without noticing it, designers will most likely be doing a huge

amount of more or less wasted work because the design will not fulfil customer needs (what's) as effectively as it could have been.

Since launching, AD has been applied for multiple purposes. Suh (2001: 192, 239, 301, 341, 376) introduces AD applications for systems, software, manufacturing systems, materials & materials-processing techniques and product design. Cebi & Kahraman (2008: 411) include also Quality System Design, Supply Chain Management, Civil Engineering Problems and Environment Problems at their conclusion of applications with AD in scientific papers. Multi-purpose use of AD is due to its nature. As a theoretical framework with its not-too-structured process, AD provides design system that could be easily adjusted to different purposes. Also, benefits of AD have been established by multiple authors, such as Ogot (2011: 736) who states that benefit of AD "lies in the problem identification and formulation steps". Not only can AD be used to create new designs for all applications mentioned before, but also to improve existing designs (Morrison, Azhar, Lee & H.Suh 2013: 712).

Axiomatic Design method is a theoretical framework, that has few key elements that will be explored later in upcoming sub-chapters. Different authors explain basics of AD in a slightly different order, but it usually starts in either domains, such as with domains (or concept of domains) as with Suh (2001: 10; 2005: 20-21). Another approach is to start with axioms as done e.g. by Suh (1998: 189). Domains is more popular to start explaining with, and in a way easier because it is the map of design process that axiomatic design follows. Axioms give framing to these domains, rules that they should follow in order to give a good design. After explaining the concept of domains, it is reasonable to go a mapping process between different domains (Suh 2001:14-15). A mathematical model of mapping involves usually presenting the first axiom, also known as Independence Axiom.

After exploring mapping and Independence Axiom, that usually involves explaining three different types of design, the next step involves exploring hierarchy of domains and how

those domains are decomposed into smaller parts, in hierarchic way. This is presented by Suh (2001: 30), Cebi & Kahraman (2008: 412) and many other authors. Finally, the second axiom, known as an Information Axiom, is explained. Use of this axiom in the research has usually been rarer than use of Independence axiom. This can most clearly be seen from previous study by Kulak, Cebi & Kahraman (2010: 6710). The rarer use of the second axiom is mainly due to the purpose of the axiom: it is needed to be counted mainly if the first axiom produces multiple equally good solutions, and out of them the best design must be found (Suh 2005: 30).

Mathematical models have been launched for both Independence and Information Axioms. These models were presented by Suh (2001: 18 39). In following chapters, brief view of these models is presented to provide a needed knowledge to understand some findings of delivered Systematic Literature Review. Chapter 2.4 is presents mathematic model for Independence Axiom and different types of designs, and chapter 2.6 is giving a brief outlook of Information Axiom in general, its mathematical modelling included.

2.2 Domains

Four domains, or concept of four domains is one of the key concepts of AD (Suh 2005: 20). According to Suh (2001: 10), design world "involves an interplay between '*what* we want to achieve' and '*how* we choose to satisfy the need (i.e., the *what*)'." Those "*what's*" and "*how's*" can be divided into four domains, as presented in figure 1 below (Suh 2001: 10-11). These four domains are (Suh 2001:11)

1. Customer domain involving Customer Attributes (CAs)
2. Functional domain involving Functional Requirements (FRs)
3. Physical domain involving Design Parameters (DPs)
4. Process domain involving Process Variables (PVs) (Suh 2001: 11).

As concluded by Cebi & Kahraman (2008: 412), left-side domain always defines *what* is wanted to achieve, when right-side domain specifies *how* it is selected to be achieved.

This decomposition process between domains is also called mapping, and is illustrated with interactive arrows between domains in figure 1 below.

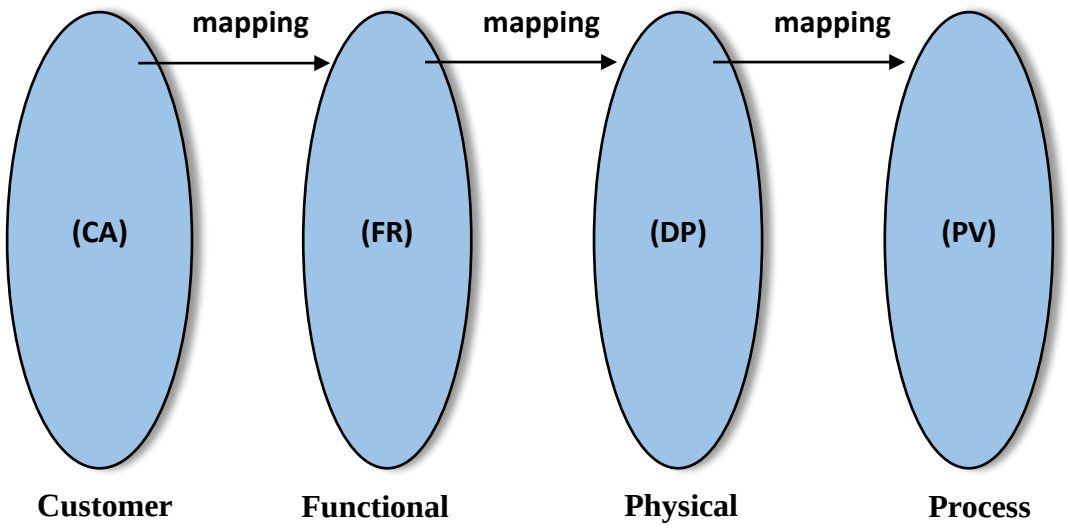


Figure 1. Four domains of the design world (Suh 2001: 11)

An example of what different domains mean in different applications is presented on table below (Suh 2001: 12). This delivers a clear example of what kind of differences CAs, FRs, DPs and PVs might have in different applications. It is noticeable, that after publishing of "Axiomatic Design: advances and applications" (Suh 2001), some authors, such as Cebi & Kahraman (2008: 411), have suggested more applications in addition.

Table 1. Characteristics of the Four Domains of the Design World for Various Designs: Manufacturing, Materials, Software, Organizations, Systems, and Business (Suh 2001:12)

	CUSTOMER DOMAIN (CA)	**FUNCTIONAL DOMAIN (FR)**	**PHYSICAL DOMAIN (DP)**	**PROCESS DOMAIN (PV)**
MANUFACTURING	Attributes that customers desire	Functional requirements specified for the product	Physical variables that can satisfy functional requirements	Process variables that can control design parameters

MATERIALS	Desired performance	Required properties	Microstructure	Processes
SOFTWARE	Attributes desired in software	Output specification of program codes	Input variables Algorithms Modules Program codes	Processes Subroutines Machine codes Compilers Modules
ORGANIZATIONS	Customer satisfaction	Functions of the organization	Programs Offices Activities	People and other resources to support programs
SYSTEMS	Attributes desired in the overall system	Functional requirements of the system	Machines Components Sub-components	Resources (Human, financials etc.)
BUSINESS	ROI	Business goals	Business structure	Human and financial resources

2.3 Mapping between domains

As mentioned in chapter 2.2, design process in general can be seen as a set of "*what*" and "*how*" questions, where designers or design team is aiming to find the best answers to said questions (Suh 2001: 10-11). As presented in figure 1 above, according to Suh (2005: 21), mapping process is a left-to-right approach between four domains. At first domain, customer needs or Customer Attributes (CAs) must be established. Usually this has to be done by co-operating with customers and marketing department (Suh 2001: 14). Then sais CAs need to be transformed into Functional Requirements so, that for each CA there is a matching FR (Suh 2005: 22). According to Suh (2005: 22), this should be done in a "solution-neutral environment" which means defining possible FRs without even thinking existing solutions. This ensures final selection to be best imaginable design and avoids it to be biased by possible end-solution ideas. Setting rights FRs is crucial, because according to Brown (2005: 189), quality of selected FRs defines the quality of final design. Final design, on the other words, cannot be any better than selected FRs.

Mapping process is typically one-to-many process, where for each CAs there are multiple possible FRs, each FRs there are equally many possible DPs etc. (Suh 2005:22). Mapping process is a core process where the design is happening, but it requires use of other tools of AD. Especially use of two axioms is important to select the best design and decomposing mapped requirements into smaller parts for desired design (Suh 2005: 22).

2.4 Independence Axiom and three main types of design

As Suh defines (2005: 21), Axiom is "a fundamental truth that has no counterexamples or exceptions. An axiom cannot be derived from other laws or principles of nature". In a process of mapping, when selecting appropriate design, there should be only one FR matching each CAs (Suh 2001: 14). Furthermore, there should be individual DP for each defined FR (Suh 2005:23). According to Suh (2005: 23), selected solution (e.g. FR for CA), should not affect any other solutions. This is principle of first axiom, the independence axiom. According to Suh (2001: 16)

> *Axiom 1: The Independence Axiom. Maintain the independence of the functional requirements*

If there are multiple solutions for design that all fulfil CAs with different FRs, best FRs are those that effect other FRs as little as possible or none at all. This brings us to the mathematical model of mapping process where independence axiom is applied. According to Suh (2007: 105), mapping process between domains can be presented as a function of two vectors, where relationship of vectors can be presented as following:

$$\{FR\} = [A]\{DP\} \quad (1)$$

This equation (1) also stands as a design equation of a product where FRs are forming vector {FR} (Suh 2007: 105). Here [A] stands for design matrix and can therefore be

presented as a matrix from as following as per equation (2), presuming that there are three FRs with three matching DPs (Suh 2001:18):

$$[A] = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \quad (2)$$

Design matrix can have roughly three different kind of designs. Design can be either uncoupled, decoupled or coupled (Suh 2001: 19). Ideal design in a form of independence axiom is a design where $A_{\mathrm{ij}} = 0$ always else than when i = j (Suh 2001: 19). Matrix that would form out of this equation is a diagonal matrix, and design that it presents is called uncoupled (Suh 2001:19). A design matrix from equation (2) of uncoupled design is presented in equation (3) below:

$$[A] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3)$$

Where zero indicates no correlation and number one indicates a correlation. This ideal design cannot always be reached in a design process. Instead, designers usually have either of the following designs when planning real world designs. A triangular design, presented below at equation (4) according to Suh (2001: 19), is also accepted as a form of good if not ideal design:

$$[A] = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix} \quad (4)$$

Triangular matrix can be either Lower Triangular (LT) or Upper Triangular (UT) form (Suh 2001: 19). In both matrices, independence axiom can be satisfied if DPs required by FRs are in specific sequence, so that either all the values above (in case of LT matrix) or below (in case of UT matrix) equals zero (Suh 1995: 258).

If in a design matrix there are correlations both above and below diagonal, design is called coupled design (Suh 2001: 19). Coupled design does not fill requirement of

independence axiom. Problem with coupled design, according to Suh (2001: 21), is, that even though it can provide unique solution with right values for FRs, it has a potential to generate multiple conflicts. For example, if one FR is changed, the whole design needs to be re-designed because that FR has been affecting all other FR's.

$$[A] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \quad (5)$$

A simple example of axiomatic design theory in practice is given by Functional Specs INC (2018). A simple, every day-use item, water tap, was used to demonstrate principles of AD and information axiom. Most customers require two functions from water tap: They need to have water flown when needed, and also mostly they want to have water in adjustable temperature. Therefore, FRs could be formed as following:

FR_1 - Adjust water flow
FR_2 - Adjust water temperature

Design team working with the problem found two possible solution. Either separate adjustments for hot and cold water as in figure 2 below or a mixer which adjust flow with vertical movement and temperature with horizontal movement as in figure 3 below.

Figure 2. Water tap with separate adjustments (FunctionalSpecs.INC 2018)

Figure 3. Water tap with mixer (FunctionalSpecs.INC 2018)

If problem is formed as a design matrix according to principles of AD, design parameter DPs would be formed as following:

DP_{11}- an adjustable valve for cold water

DP_{12} - an adjustable valve for hot water

DP_{21} - vertical adjustment for water flow

DP_{22} - horizontal adjustment for water temperature

Design matrixes are then as following, where matrix $A_1$is formed with $DP_{11}$and DP_{12}, and matrix $A_2$is formed with DP_{21} and DP_{22}. Then,

$$A_1 = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \quad (6)$$

because both DP_{11} and DP_{12} have correlation with both functional requirements. Both valves effect equally to the flow and temperature. According to axiomatic design, A_1 is coupled design and do not fill requirement of independence axiom. Therefore $A_2$is formed with DP_{21} and DP_{22}, and design matrix is as following:

$$A_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (7)$$

because design parameters DP_{21} and DP_{22} affect individually each functional requirement. Furthermore, A_2 is a diagonal matrix, so design of A_2 is decoupled which is ideal design according to Suh (2005: 25).

2.5 Decomposing

Mapping process in Axiomatic Design always starts with defining Customer Attributes, CAs, and then defining Functional Requirements that match with them, as mentioned earlier. However, the more complex the project is, the wider are usually CAs. For that reason, FRs and all matching DPs and PVs that are equal to the DPs have to be decomposed into smaller, more manageable pieces (Suh 2001: 29). This is essential for detailed and, therefore, more functional design. In example, if FR_1 is "to move forward", the design in detailed level would be completely different whether DP_1 would be selected as a car or as a horse (Suh 1995: 258).

Decomposition process should be done by *zigzagging* between the domains for very same reason explained in previous example (Suh 2005: 27). This is illustrated in figure 4 below. It is noticeable, that even though decomposing process forms a hierarchy, both domains should be involved so that first *DP* is selected for *FR*, then *FR* is decomposed for sub-FRs, in this case FR_1 and FR_2 and matching DPs are then formed based on these (Suh 2005: 27). Through zigzagging process, design functions and matrices are needed to be formed to ensure fulfillment of the independence axiom (Suh 2001: 30). As per requirement of independence axiom, design matrices need to be either diagonal or triangular.

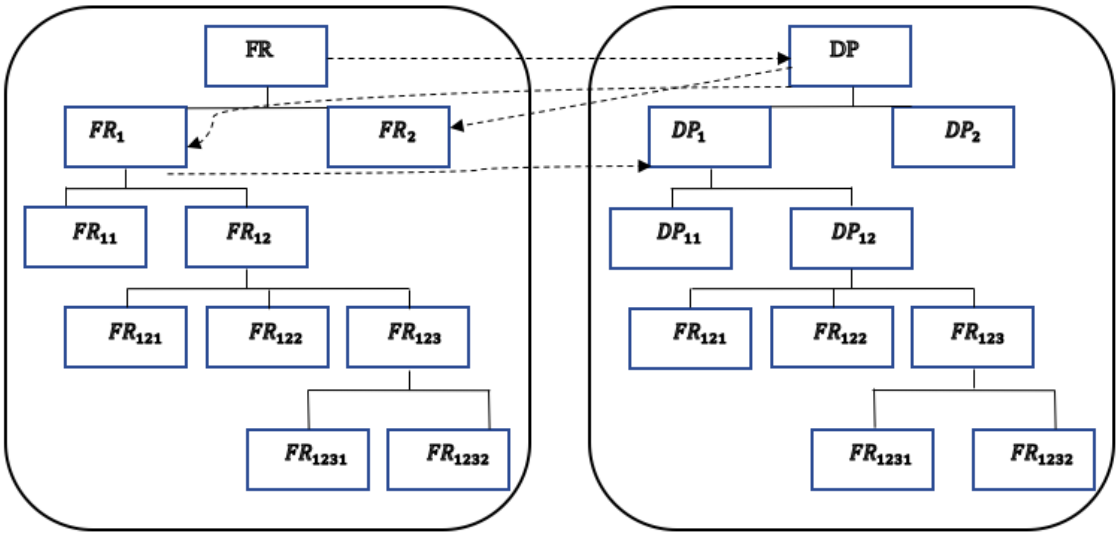


Figure 4. Zigzagging to decompose FRs and DPs and create the FR and DP hierarchies (Suh 2005: 27).

In a decomposing process, hierarchy ends with “leaves” (Suh 2005: 27). They are level of decomposition, that is not needed to be decomposed any further for good design. For example, the case illustrated above in figure 4, FR_2, FR_{11}, FR_{121}, FR_{122}, FR_{1231}, FR_{1232} and matching DPs are so called “leaves” of this particular design.

2.6 Information Axiom

In AD, there is possibility and even likelihood, that design team will come up with two or more equally good decision equally satisfying the independence axiom (Suh 2005: 30). In such case, the best design would be one that has highest probability to succeed, meaning the highest probability to fill all FRs (Suh 2005: 30). According to Suh (2001: 39; 2005: 31), a design that has the smallest information content I_i is optimal design. The second axiom, Information axiom, is formed as following (Suh 2001: 16)

Axiom 2: The information Axiom. Minimize the information content of the design

Information content I_i of design can be formed into a mathematic equation with probability P_i of satisfying FRs as following (Suh 2001:39)

$$I_i = log_2 \frac{1}{P_i} = -log_2 P_i \quad (8)$$

In a design situation, information is given by two ranges: allowed tolerance (design range) and range that system is capable of delivering (system range) (Kulak, Cebi & Kahraman 2010: 6706). An information content is illustrated in figure 5 below (Kulak & Kahraman 2008: 418). Area within common range demonstrates an area where design is acceptable. Therefore, P_i equation can be demonstrated as below (Kulak & Kahraman 2005: 196)

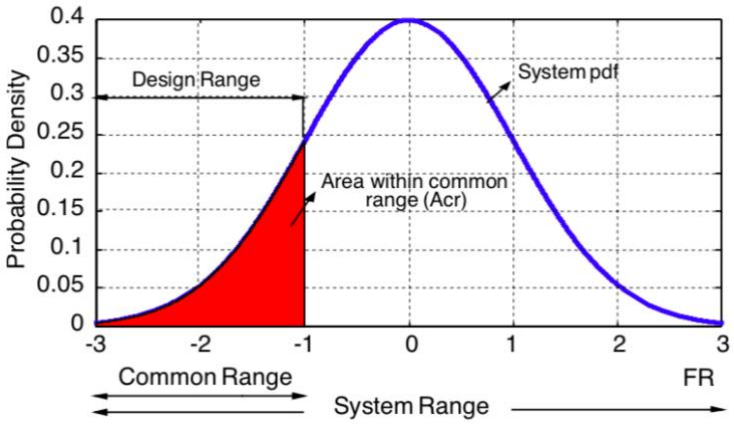


Figure 5. Design range, system range, common range, and system pdf for FR (Kulak & Kahraman 2005: 196)

2.7 Crisp and Fuzzy Axiomatic Design

As seen from previous study by Cebi, Kulak & Kahraman (2010: 6710), an independence axiom is more usually applied in a literature than information axiom. This is not only due to the design process of AD where independence should be fulfilled first and then, if there are still multiple equally good designs, information axiom should be used to decide

which is the best design. It is also because information axiom is more complex to use in practice due to the fact that information content of design, especially in a fuzzy decision making, is usually hard to define (Kulak & Kahraman 2005 a: 192). Also, real world problems can be complex due to objectives that might be conflicted with each other and measured with different scales (Kulak & Kahraman 2005 a: 192). Kulak & Kahraman developed a crisp axiomatic design model (2005 a:197-198 & 2005 b: 418-419) to convert fuzzy problems into a more manageable model.

According to Kulak & Kahraman (2005 a: 197-198), in case of fuzzy AD (e.g. either incomplete information of system or fuzzy attributes, such as linguistic terms), data should be first transformed into fuzzy numbers. Then fuzzy numbers or sets are transformed into crisp scores, to be able to handle fuzzy information. Said crisp scores are usually expressed “over a number”, “around a number” or “between two numbers” approach (Kulak & Kahraman 2005 b: 412). These will form a set of triangular/trapezoidal fuzzy numbers (TFN), and information content can be then equaled as following function (Kulak & Kahraman 2005 b: 422):

$$I = log_2\left(\frac{TFN\ of\ system\ range}{Common\ area}\right) \tag{10}$$

As a graph, this can be expressed as per figure 6 below, where common area has been highlighted with grey color in between of fuzzy values converted into crispy ones:

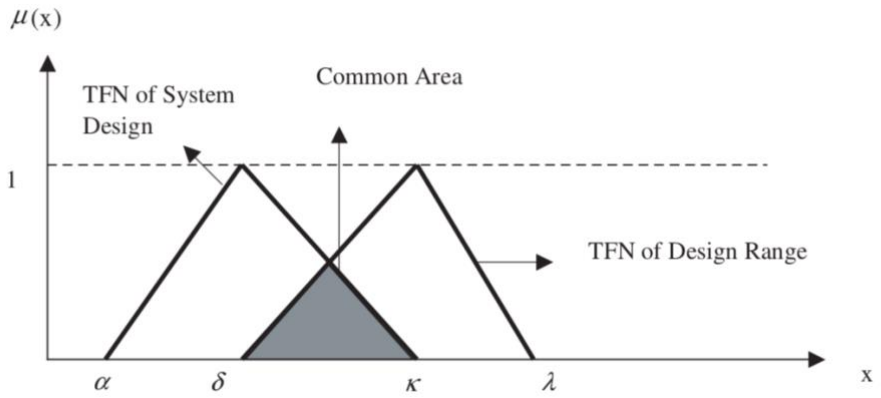


Figure 6. The common area of system and design ranges. (Kulak & Kahraman 2005 b: 198)

2.8 Applications of Axiomatic Design

Since introducing AD to the public, researchers N.P.Suh in front have been publishing multiple papers researching Axiomatic Design applications for different purposes. In this paper, applications of AD have been divided into seven different categories: Product design, System design, Manufacturing system design, Software design, Decision making, Services and Others. Applications of AD for different purposes are shortly discovered below in individual paragraphs to deliver a brief information for the actual systematic literature review that follows this categorization.

A product design can be seen as a system design issue, that includes both designs of hardware and software systems (Suh 2001: 376). When products are planned applying principles and processes of AD, it is common to be combined with other design methods, such as conceptual design or quality function deployment (Du & All 2013: 81). As Suh concludes (2001: 381), in product development basic principles of AD exists and are important to follow on purpose of completing a good design. This means, according to him, couple of important reminders of AD (Suh 2001:381) as listed below:

i) Importance of Defining FRs first. Final design cannot be any better than defined FRs.
ii) Avoid coupled designs. Coupled design that will be then randomly decomposed to create FR/DP/PV hierarchies will multiple unwanted dependences.
iii) System integration while developing product, not separately afterwards
iv) Innovative products. To not get stuck too much in what has been used to do.

As Suh emphasizes, AD can be also used to improve existing product, for example together with different market researches that define CAs desired for improved product (Suh 2001:385). Also in this phase, most important step is defining FRs and mapping them into PVs. According to Suh (2001: 385), in large companies that make market-research based developing, marketing department should define customer needs or functional requirement, but only them. Engineers should take care then of further design.

Axiomatic Design for System design was defined by Nam P. Suh and made known by public 1998 when his article “Axiomatic Design theory for Systems” was published. This theory was a general theory of AD for System design, although later more detailed theory for Manufacture systems was developed as well by Suh. Also, specific complexes such as machines, software’s and organizations are seen as systems (Suh 1998: 189). System is usually understood as a complex combination of hardware, software and people such as a manufacturing system (Suh 1998: 190). This is explored in following paragraph in more detail. A system design is important to complete as a whole to avoid mistakes of adding or designing sub-systems or separate parts into a system (Suh 2001: 195). A benefit of AD methodology when designing systems is forming up-to-down designs (Suh 1998: 189). A mapping process in system could also be seen as creating the system architecture (Suh 1998: 191). Principles of AD, specifically two axioms of AD are valid in AD for systems as well. Suh also developed a set of theorems specifically for design for systems and organizations in additional of theorems for general design (Suh 1998:208-209).

Manufacturing system design theory for Axiomatic design is in many ways similar to a system design theory. As well as the other applications, also Manufacturing system has to be designed due to two axioms of AD (Suh 2001: 306). Basics elements of manufacturing systems are people, things and information, which all should be taken into consideration when planning manufacturing system (Suh 2001: 307). According to Suh (2001: 309,317) manufacturing systems can be divided into two main groups: *fixed* and *flexible*. Design of manufacturing systems should take into consideration which of said main groups the particular system is presenting.

Benefits of applying AD into Software design are that it provides proper interrelationships and arrangement among modules, and that it is relatively easy to change (Suh 2001: 239). According to Suh & Do (2000: 95), need for AD applications in software engineering was discovered due to costly errors of poorly planned designing

processes. Suh and Do (2000: 100) even state in conclusion of their paper that “Software development can be done efficiently in a shortest possible time with full confidence when it is done with Axiomatic Design.”.

Multiple studies such as Conçalves-Coelho & Mourão (2007) and Deng & Jiang (2018) has studied applying AD into decision making. Conçalves-Coelho & Mourão (2007: 88) summarize that AD gives a decision-making tool for engineers to handle somehow loose directives of Design for Manufacturing. On their behalf, Deng & Jiang (2018: 19-21) have been using AD to develop a Dempster-Shafter Evidence Theory to optimize results for decision making within the discussed theory. Both studies conclude that AD can be viewed as an effective tool for decision making due to framework that use of two axioms provides.

There are very little publications of Axiomatic Design for services. Most typically inventions have been a part of a service process, where AD has been applied to develop such invention like a system or a tool to support a service, e.g. a web service platform (Chiara & All 2018: 2). Chiara & All (2018:10) emphasized that a pro-activity and ability to adjust a service system to changing customer needs are most significant benefits of application of AD. In addition to all the six applications defined, other-category was included as per previous study (Cebi, Kulak & Kahraman 2010: 6707), for those findings that do not fit clearly any of the earlier categories.

3 RESEARCH METHODOLOGY

In this chapter, a research method that is applied in this research is briefly explained. At first, in chapter 3.1 literature review – background related on Axiomatic Design is explored. Next, sub-chapters 3.2 and 3.3 explain background and theory of Systematic Literature Review (SLR). Rest of the chapters, from 3.3 till 3.7 give a comprehensive view how the research process has been done: how SLR has been applied in-practice on this study and in what extent; how research questions have been formed and what kind of selection criteria has been used to narrow amount of studies selected as a part of this SLR and finally, how search process was carried out and what are results of said process. Aim of this chapter is not only to deliver transparent study, but also allow future researchers to repeat partially this approach in possible following research.

Selected research methodology, Systematic Literature Review, is a study-of-studies: it evaluates existing studies based on research question and evaluation criteria specified when defining SLR process. In general, SLR can be seen as a *nomothetical* studies. On the other words, the type of studies that are defining how things are currently (Helo & all 2019:15). On the other hand, SLRs again in general and specifically in this study, don't aim to theoretical development. In the axis of *theoretical–empirical* this research is defined as *an empirical study.* Hence, this research is concluded to be *a nomothetical empirical study*.

3.1 Literature reviews of Axiomatic Design

As explained in introduction, there are very few literature reviews written of Axiomatic Design and related academic publications. This, as discussed before, is also one of the key reasons why this methodology and topic was selected as a topic of this research. There are completely three literature reviews carried out that are handling Axiomatic Design. Each of these literature reviews is explained in its own paragraph below.

The first of the three articles goes by subtitle “Applications of Axiomatic Design in Manufacturing System Design: a literature review” (Rauch, Matt & Dallasega 2016). As the title reveals, authors are collecting and studying papers that are especially focusing on manufacturing system design. Interestingly, authors focus in this paper as well in some categorizations, that are similar to the ones used in this research: they divide articles by use of axiom. Different from this study, authors use categories. In addition to “Independence” and “Information”, they have “Both” and “No focus” also as options. With this article, also dividing based on method has been done, on the other words articles have been categorized into “theoretical development” and “application of Axiomatic Design”. Aside from that authors use more specific categorizations that have not been applied in this paper. E.g. based on main specific topic inside manufacturing system design, handled domain level and country of origin of authors.

The second of the three papers carries out a literature review of applications of Axiomatic Design for Human safety in Manufacturing systems (Sadeghi, Houshmand & Valilai 2017). Having a more specific definition of interest than previous article by Rauch & All (2016), paper by Sadeghi & All (2017) is dealing with smaller number of studies as well. All together 15 papers were selected into this literature review. Authors divided found articles into three main groups, these being ergonomic design, human-computer interactions and safety design in a design process. The paper concludes that AD benefits for better design when used to design for safety in context of Design for Human Safety-framework. Some gaps within current framework were also identified such as links between DP-FR hazards in a design process.

Last article of three literature reviews is most significant for this paper. It is a literature review of Applications of Axiomatic Design written by Kulak & All (2010). This study does not explore specific area of application of AD, but rather views all the publications related on AD between 1990-2009 and collects them together categorizing articles based on applied axiom, application type, applied method and evaluation type. The current

research has been done as a continuum for this study. Similar evaluations and categorization has been used, as well as search methodology for recent articles.

3.2 Background of Systematic Literature Review

Roots of Systematic Literature Review lay firmly on medical sciences, on l980s (Stapic & All 2016:104). It is, as Mariano et all (2017: 2) conclude, a method that collects, evaluates and summarize literature related on certain research question. SLR is considered as an exact, reliable and repeatable method (Stapic & All 2016 :104) and therefore it has spread from medical sciences to other applications since it was invented. There are studies guiding the use of SLR in example for Software Engineering (Kitchenham & Brereton 2013; Stapic & All 2016; Budgen & Bereton 2006), obviously Medical Sciences (Schweizer & Nair 2017; Nightingale 2009) and Bioinformatics (Mariano & All 2017). Although there is no specific study of how to apply SLR into AD, principles of SLR can be applied in virtually any are of scientific research.

Significance and popularity of SLR according to many authors such as Mariano & All (2017:2) and Nightingale (2009: 381) is due to its ability to prevent bias of traditional literature reviews. In a non-systematic review, authors opinions and preferences may have an effect on selected studies: it is more likely that authors will prefer studies that support their assumptions of results (White & Schmidt 2005: 54). For medical sciences, first institute delivering out SLRs on many specific areas was founded in 1993 (Nightingale 2009:381). According to Nightingale (2009:381), this is due to results in a research conducted in 1992 by Lau, Jimenez-Silva et all. that found out from a specific therapy had had significant evidence 13 years before it was accepted officially, only the evidence had been divided in multiple research papers where individually the amount of evidence had been non-significant. In other words, use of that specific therapy was unnecessary delayed for 13 years. That delay could have been avoided with conclusion of those papers, in the other words with carrying proper SLR.

3.3 Systematic Literature Review process

Definition of SLR's structure vary slightly depending on area of application. However, there are three main steps that are mutually included into instructions of how to deliver a SLR process (Budgen & Bereton 2006: 1052; Brereton, & All 2007: 572; Stapic & All 2016: 105; Kitchenhamn 2004:3) . These steps are:

Planning the review

Conducting the review

Reporting the review

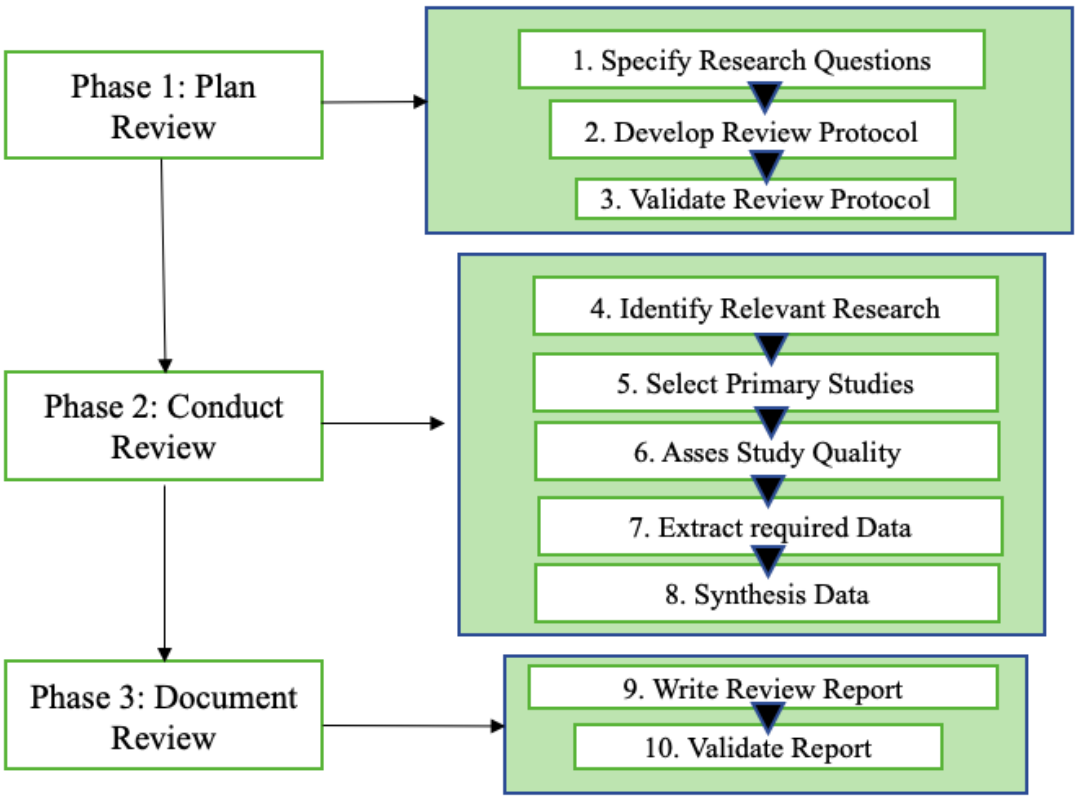
As mentioned above, different authors might vary sub-steps of the process depending on the specific area of research. Stapic & All (2016: 105) conclude three-step process of SLR as following, with described sub-steps as in table 2 below. In this table, planning the review starts with identification the need of a review. Planning-step has also couple of recommended phases such as evaluating of a review protocol and the report. All three main phases of SLR process are generally explained, and furthermore detailed in chapters 3.3-3.7.

Table 2. The review Process (Stapic & All 2016: 105)

Phase 1: Planning the review
Identification of the need for a review
Commissioning a review (optional)
Specifying the research question(s)
Developing a review protocol
Evaluating the review protocol (recommended)
Phase 2: Conducting the review
Identification of research
Selection of primary studies
Study quality assessment
Data extraction and monitoring
Data synthesis

Phase 3: Reporting the review	
	Specifying dissemination mechanisms
	Formatting the main report
	Evaluating the report (recommended)

Some authors, such as Brereton & All (2007: 572) present review process more as a process flow. Also, the process varies a little compared to model presented above. However, main steps and critical parts are similar. Both are presenting review questions as a starting point of forming the actual research. Stapic & All (2016:105) have the identification process and optional commissioning before that. Next step for both models is to develop a review protocol that will be used to guide the whole phase 2 – *conducting.* Phase 2 is matching for both authors, and phase 3 is focused on writing the main report of the review and validating it. In this paper, relevant model in scope of resources, most importantly time and human resources (with only one person working with the research), is to follow process flow by Brereton & All (2007: 572), as in Figure 7



below.

Figure 7. Systematic literature review process (Brereton & All 2007: 572)

Planning a SLR process is what following chapters, chapters 3.3-3.7 are explaining. Research questions and Protocol (e.g. scope, strategy and criteria) are framing rest of the SLR, so they need to be carefully determined. As Brereton & All (2007: 572) summarize, a selection of primary studies is determined in a planning process, most specifically, in a protocol of a review. Review itself, being a study of studies, presents a secondary study. Stapic & All (2016: 106) state that specifying of the research question(s) is the most important part of planning process and entire review. That is, because it is the base of all activities defined later. Usually there are either multiple research questions or a single question that has been decomposed into the smaller sub-questions (Stapic & All 2016:107). Equally important phase of planning is developing a review protocol, specifically to ensure that the review will be systematic and not influenced by researcher's personal views (Nightingale 2009: 381).

When conducting a SLR, a protocol of review defined in phase 1 should be followed. Tools to help conducting SLR, such as PRISMA evaluation technique for primary studies, have been developed and widely used (Booth & All 2016: 287-289). Conducting SLR requires reading multiple papers of the selected topic, and evaluating them according to defined criteria (Stapic 2016: 108). Basically, the conducting phase should follow guidance defined in a planning phase (White & Schmidt 2005: 56). When primary studies have been evaluated according to the criteria of created protocol, data from the studies should be extracted and synthetized for further analysis (Schweizer & Nair 2017: 1293). A recommended form is a table, at least to summarize primary studies, but also in qualitative studies to present findings (Stapic 2016: 108).

Final stage of SLR process is reporting, or documenting the review. In this phase, data extracted and synthetized previously is analyzed and concluded into a report that is the core of the review, for presumed audience (Booth & All 2016: 295) (White & Schmidt 2005: 58). It should present findings, possible correlations, gaps in research and need of

further research in certain question (Woods 2003:7). Also, when presenting results, search process should be explained to ensure transparency of the research process (Stapic 2016:114-115).

3.4 Research questions

When planning SLR for publications of AD, a study published in 2010 “Applications of Axiomatic Design” (Kulak, Cebi & Kahraman 2010) was explored. Even though this study does not mention a systematic literature review in its methodology, a conducting has clearly characters that fulfill requirements of SLR. Author states at their abstract that the paper was written to fulfill a gap of comprehensive literature review of applications of AD in past twenty years (Kulak, Cebi & Kahraman 2010: 6705). Hence, when planning current SLR, previous work of Cebi & All was a natural starting point: to provide a continuum to the said research. However, since research of AD has been more active since 2010 than before last review was published, time cap was decided to be bit more limited into past five years (2013-2018). For collecting and synthetizing information, same head categories were decided to use with slight modification of sub-categories: type of axiom, application area, method and type of evaluation (Kulak, Cebi & Kahraman 2010: 6707).

As a continuum of previous literature review by Kulak & All (2010), research question is reasonable to be quantitative as were results of that study. Furthermore, it is reasonable to compare possible findings of this study to the previous one. Therefore, research question was formed as following:

> *RQ1: Has there been a significant change in application of Axiomatic Design in past five years compared to the literature review by Kulak, Cebi & Kahraman (2010)?*

It is reasonable to decompose research question into three smaller parts according to findings of previous study and of personal interest. Thereby the research question RQ1 is decomposed as following:

RQ1.1: Has there been change in proportion in use of information / independence axioms?

RQ1.2: Has there been significant change of applications of Axiomatic Design?

RQ1.3: What is proportion of services in applications of Axiomatic Design within research range?

Last question was added out of personal interest, to find out is there any significance research published on AD applications in services within last five years. Interestingly, there was no mention of services or their proportion in previous literature review. For main research question and sub-questions RQ1.1 and RQ1.2, a qualitative comparison with pie charts as used in previous paper is used (Kulak, Cebi & Kahraman 2010: 6710).

3.5 Research Scope

According to Booth & All (2016: 99), defining research scope is an important step of creating protocol for SLR. With good, clear scope, selection criteria will be easier to set. Having a clear scope and in such way, clear protocol for review is crucial for avoiding possible bias and keeping review systematic (White & Schmidt 2005: 55-56). There are tools to evaluate research questions and scope, such as PICOC as per table 3 below (Booth & All 2016:86).

Table 3. The elements of PICOC (Booth & All 2016; 86)

Population	Who or what is the problem or situation you are dealing with? In a human population, for example, which age, sex, socioeconomic or ethnic groups are involved? What are the technical terms, synonyms and related terms?
Intervention OR Exposure	In what ways are you considering intervening in the situation? What sort of options do you have for tackling the problem? For example, this could be an educational intervention such as online tutorials on plagiarism (population = undergraduate students)
Comparison	What is the alternative? This is optional. For when you wish to consider, for example, the effect of two or more interventions, comparing their outcomes possibly in terms of what they deliver and/or cost. So, you may want information on the relative merits of: • buses versus trams for urban congestion; • natural versus chemical methods of agricultural pest control • surgery versus drugs for an illness
Outcome(s)	How is it measured? This may be more difficult to identify: you have a technical terminology for your problem and a range of management options, but what you do want to achieve? This stage does, however, focus your mind on what your desired outcome(s) might be and how you will assess the impact – what you are going to measure and how
Context	What is the particular context of your question? Are you looking at specific countries/areas/settings?

PICOC is, according to Stapic & All (2016: 106), related to research question. In case of this research, main research question determines first three phases of PICOC. It has Population (= research papers with AD applications within past five years), Intervention (Qualitative, statistical comparison of findings with previous ones), Comparison (Papers of similar applications but with other design methodologies). As an outcome, in this case there is straight-forward numerical and graphical comparison between proportions of different axioms as in RQ1.1 and different applications as in RQ1.2. As a context, in this research findings of applications with services are separated into a sub-category of applications and discussed in analysis (chapter 4) and discussion (chapter 5). Expected findings in a context are as well awareness whether there is a further need of research of Axiomatic Design in services, and if so, what kind of research this field is specifically lacking.

3.6 Search Strategy

In a Systematic Literature Review an important value in a search strategy according to Booth & All (2016: 109) is sensitivity. This means maximizing the change to recognize all relevant literature to the topic. However, as in any project, also in a SLR resources and time define extent of the research. Also, as a continuum of previous SLR by Cebi, Kulak & Kahraman (2010), a search strategy that is based on their experiences and results is recommended. Keywords to the search then were set, according to Cebi, Kulak & Kahraman (2010: 6716) as following:

Search term I: “Axiomatic design”

Search term II: “Independence axiom”

Search term III: “Information axiom”

To ensure all relevant results to be found, searches were defined to be inclusive. On the other words, all of the searches were defined so that any of the three search terms found would be count as a result.

In a search process, couple of tools suggested by authors have been applied for this study. Booth & All (2016: 288) as well as Nightingale (2009: 383) explained criteria for searching relevant primary studies, called PRISMA. This will be explained in following chapter 3.6. In a paper of Wood (2003: 5) was requested following format for SLR search findings & selection as per figure 8 below where RCTs stand for Randomized Control Trials. To form a first phase, database and reference list will be decomposed in smaller pieces according to the accessibility, that is, to the databases that were able to access as a student of University of Vaasa.

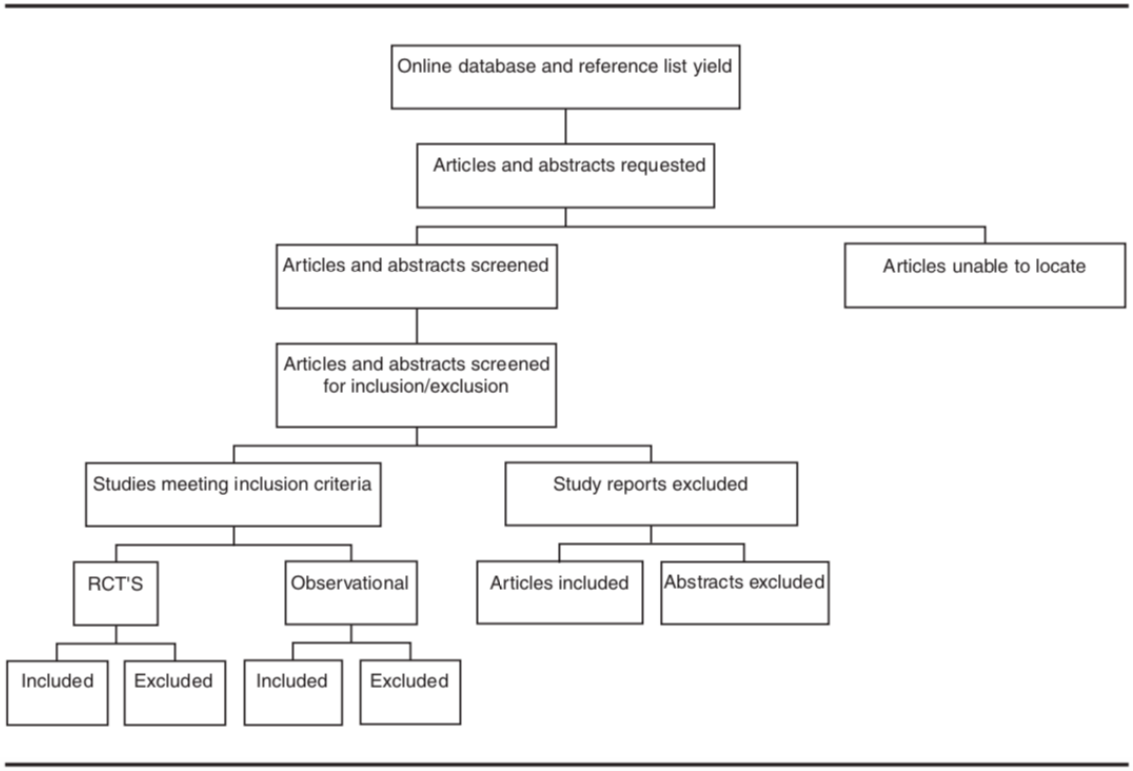


Figure 8. Search and retrieval process. (Wood 2003:5)

Below in figure 9 are listed sources for research. Actual search process is described in a chapter 3.7 and further narrowing is evaluated in chapter 3.6 where selection criteria is established. Another source is to explore all articles of International Conference of Axiomatic Design (ICAD), that are available on world wide web (FunctionalSpecs.INC **b**, 2018). It is noticeable that these articles are only available until 2016, so articles of past two years (2017 and 2018) are not included from that source. They were needed to explore from webpages of each years ICAD conferences. It is also noticeable, that University of Vaasa's Journal search FINNA automatically excludes most of the duplicates. However, when listing findings according to sub-chapter 3.7, possible duplicates will be recognized and removed. Most likely source of duplicates is parallel use of search from journal/seminar databases and use of listed ICAD articles.

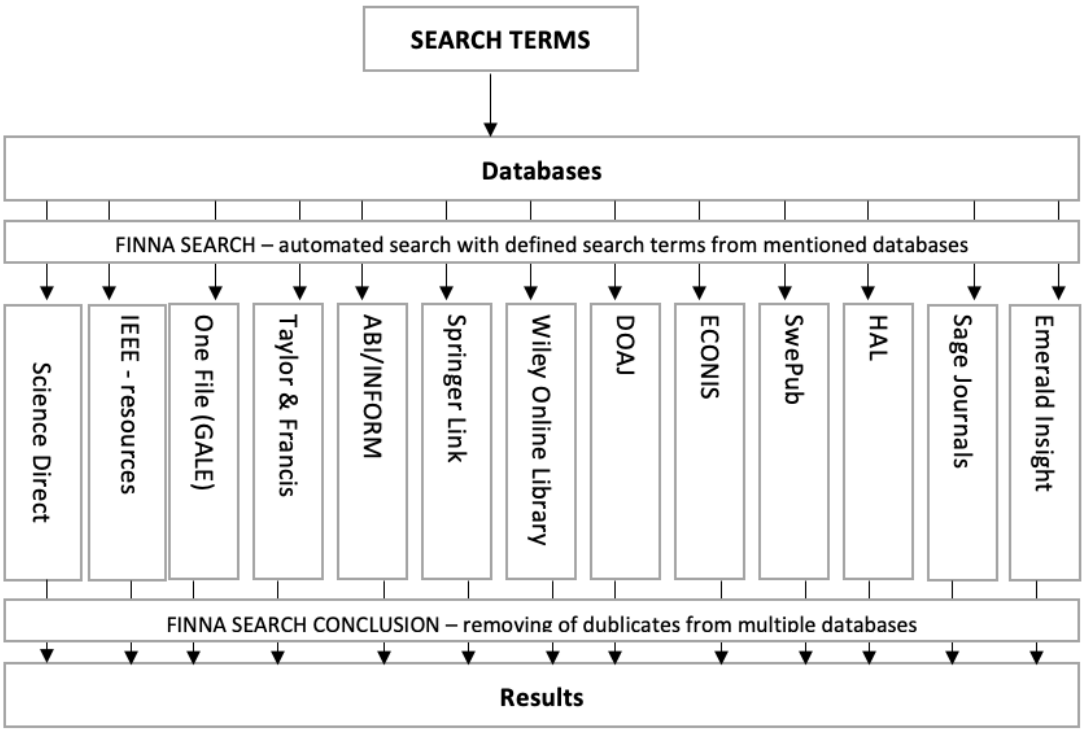


Figure 9. Search process flow from FINNA- databases

3.7 Selection criteria

Primary factor narrowing down a search scope was, as well as with previous study, a timeline which was used for research. Multiple authors, such as Booth & All (2016: 288) and Nightingale (2009: 383) suggest a selection process called PRISMA to narrow down amount of results from first hit of studies. PRISMA is a reporting workflow that contains four stages: Identification of search results, Screening of identified results, eligibility of screened results and including then results that has passed eligibility stage (Nightingale 2009: 281;283).

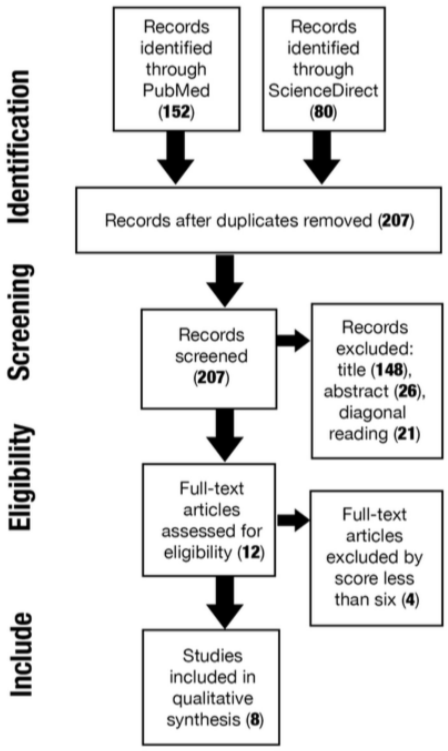


Figure 10. The PRISMA statement (Mariano & All 2017: 11)

Also approaches similar to PRISMA have been suggested, such as the one presented by Mariano & All (2017: 7). These steps are basically steps of PRISMA statement, but without the reporting requirement. They suggest a four-step system to evaluate relevant literature, including following steps (Mariano & All 2017: 7):

i) Title evaluation
ii) Abstract evaluation
iii) Diagonal reading
iv) Full-text reading

In this research following criteria has been selected, according to PRISMA statement:

IDENTIFICATION – results from FINNA database with following narrowing: instead of all result of Axiomatic Design, search was narrowed down with key word combinations “axiomatic design” OR “independence axiom” OR “information axiom” to be existing in the subject of a research. Also, time cap was narrowed down to researches published between 2013-2018. ICAD conferences were

searched between 2013-2018. Duplicates between findings are removed in this phase.

SCREENING ¬– found papers of identification state are explored by their abstract, as suggested by Mariano & All (2017: 7). Papers, that has no mention of Axiomatic Design or either of the axioms in the title or in the abstract are excluded.

ELIGIBILITY – The conclusion of each paper is read, also diagonal reading (of images, graphs and tables) is done and inappropriate studies that has not used AD in the conclusion are excluded at this phase.

FULL-TEXT READING – Rest of the papers, selected studies are read and concluded in few sentences to include into the study as in previous one by Kulak, Cebi & Kahraman (2010: 6710-6715)

3.8 Search process

According to the criteria defined in paragraph 3.6, search process was carried out in two different platforms. In a multi-database search by University of Vaasa, FINNA search as demonstrated in figure 8. On the other hand, all ICAD documents from 2013 to 2018 have been explored and collected as search results, and explored for further investigations according to procedure explained in 3.6.

A search process is following explained, step by step and with relevant numbers of found. First of all, two basic sources of articles were searched. ICAD databases had multiple articles published for each year, as listed in table 3 below

Table 4: Results from FunctionalSpecs.Inc (Online 2018)

CONFERENCE	NUMBER OF PUBLICATIONS
ICAD2013	31
ICAD2014	28
ICAD2015	45
ICAD2016	42

Since results mentioned above are from Conferences of Axiomatic Design, most likely all results are going to be valid for the survey. However, a systematic approach to evaluate articles as described in chapter 3.6 is applied for these results as well. Since no content of ICAD2017 or ICAD2018 was available from FunctionalSpecs.Inc, said two conferences were searched from official webpages of each conference. Papers of International Conference of Axiomatic Design 2017 were published in MATEC web of conferences – open access template whereas papers of International Conference of Axiomatic Design 2018 were directly available at homepage of the conference. As a result, rest of conference papers from relevant years of International Conference of Axiomatic Design were discovered as per listed below (Table 5):

Table 5: Results from International Conference of Axiomatic Design 2017 & 2018 (Mate-Conferences.org 2018; ICad2018 2018)

CONFERENCE	NUMBER OF PUBLICA-TIONS
ICAD2017	31
ICAD2018	28

After gathering together articles from International Conferences of Axiomatic Design as mentioned above, searching process continued as per chapter 3.5 and image 9 into scientific article databases of University of Vaasa. Applied search terms as per 3.5 were I: “Axiomatic Design”, II: “Independence Axiom” and III: “Information Axiom”. Search limitations were set first to limit results into publications between re-selected time frame, on the other words between publications published from 2013 to 2018. This resulted results of 1024 in search term “Axiomatic Design”, 603 results in search term “Independence Axiom” and 345 search results of “Information axiom” as per table 6 below

Table 6: Search results from FINNA-database with limited publication year and key terms

SEARCH TERM	NUMBER OF PUBLICATIONS
"Axiomatic Design"	1022
"Independence Axiom"	603
"Information Axiom"	345

After results of primary search it became clear that further limitations are required to limit final results. In order to apply them, following limitations have been set:

1) Search results are limited to include only full-text available articles
2) Search term I “axiomatic design” has been defined as a subject search term of all searches to include only relevant hits

Search limitations were applied at University of Vaasa’s FINNA article search with search term “Independence Axiom”. With applied limitations results were following as per table 7 below, search results were for search term I “Axiomatic Design” with subject set as “Axiomatic Design” 102 results, search term II “Independence Axiom” with subject set as “Axiomatic Design” 4 results and search term III “Information Axiom” with subject set as “Axiomatic Design” 32 results.

Table 7: Search results from FINNA-database with limited publication year and limited key terms

SEARCH TERM	NUMBER OF PUBLICATIONS
"Axiomatic Design"	102
"Independence Axiom"	4
"Information Axiom"	32

As per total, search results with selected SLR methodology have collected totally 343 articles at this phase. Following the selection process of final articles included into Systematic Literature Review is explained. The selection process is following PRISMA-model as per chapter 3.6 and Marioni & All (2017:11)

As per total, results of search according to pre-selected criteria at this phase were screened and possible duplicates removed. Comparison between results of ICAD-

conferences ended with zero duplicates, meaning that all results of ICAD conference publications entered into Screening-phase. From results of FINNA-search there were multiple duplicates: from Independence Axiom, none of the results were identified as duplicate. From Information Axiom, article of Chen, Xiao, Zhang, Gu & Cai (2014) was a duplicate of search result from results of Independence Axiom – search. Most duplicates were found from result of Axiomatic Design ending up completely 12 duplicate articles, one of which was found as a double-article in FINNA-database from different publications and published one-year apart and with slightly different headline but with an identical article: Farid's article of "Multi-Agent System Design Principles for Resilient Coordination & Control of Future Power Systems" (2014). In a result with total 13 duplicates removed, number of articles entering next phases SCREENING and ELIGIBILITY as per 3.6 had reduced into 330.

Screening and Eligibility - phase of SLR includes reading abstracts of papers that fulfilled inclusion criteria so far. At this phase, papers that based on Abstract or conclusion do not fulfil research criteria are excluded. In this case, research criteria, since Systematic Review is about Applications of Axiomatic Design in academic publications, either abstract or conclusion or both should give clear indication that if not primarily, Axiomatic Design should have been involved into either subject or methodology in a paper involved. Based on reviewing papers with defined criteria, number of selected articles was reduced as following. All of 205 publications from ICAD- conferences were still included into result based on their abstracts & conclusions. From results of Independence Axiom 1 article were excluded at this phase as irrelevant (articles related to other topics), from Information axiom 20 of the articles were excluded at this phase and from Axiomatic Design 16 articles were equally excluded. As a result, total number of articles included into final results of SLR research was 280 articles. Full list of articles included with review result as a simple table is presented at appendix 1.

4 ANALYSIS AND RESULTS

Chapter 4 explains how and why results of this Systematic Literature review have been explored. It highlights comparative study by Kulak, Cebi & Kahraman (2010) and its methods and explains why previous criteria and categorization has been mostly applied, and where and why there are exceptions. Further discussion of notices based on categorization criteria and possible future studies is explained more in detail at chapter 5, but they are also preliminary noted in this chapter as well. Finally, even though statistics and comparison between benchmarking study are explored in subchapters later on, they are presented purely in view of this study.

4.1 Review of benchmark study and noticeable differences

As mentioned earlier, this study is a continuum for previous study “Applications of Axiomatic Design principles: A literature review” by Kulak, Cebi & Kahraman (2010). For that reason, at the beginning of reviewing results and analysis on this systematic review, it is reasonable to have a general briefing on benchmarked study. As authors mention in their paper (Kulak, Cebi & Kahraman 2010:6705), no systematic review of Axiomatic Design was existing before their study. This did not only mean that there were no pre-set limitations on time period nor other extension of the study, but also that authors needed to establish evaluation and categorization criteria. They ended up with categorization based on the axiom each paper had been using (independence / information), type of the evaluation (crisp / fuzzy), area of application (Product design / System design / Manufacturing System design / Software design / Decision making /Others) and method (Application of AD / integrated method / theoretical development) (Kulak, Cebi & Kahraman 2010: 6707 & 6710). In this research, same classification had been used in extension of adding “Services” as one of the applications of Axiomatic Design.

In the previous study, Kulak & All (2010) presented their findings on a similar table as per appendix I. However, since they had significantly lower number of papers, all together 63, they were also able to present a summary of each paper in sub-chapters including application area of each paper (Kulak, Cebi & Kahraman 2010: 6710-6715). Due to significantly larger number of papers evaluated for this SLR, each application category of AD is presented with few case examples. However, none of the case studies are explored in detail. Furthermore, in exception of previous research, a plain review of other segments of classification is also explored. As mentioned above, these segments are axiom applied, application area as already mentioned, method and type of evaluation. Even though further discussion of results, analysis and limitations are carried out in chapter 5, significant facts are already highlighted during the current chapter as well.

Being first literature review of scientific papers of Axiomatic Design, benchmarked article made multiple notices and conclusions. Interestingly, since Kulak & All (2010) started their review from 1990s there were multiple years (1990,1991, 1999 and 2001) where only one paper was published (Kulak, Cebi & Kahraman 2010: 6711). Towards the end of the year range number of papers is noticeably increasing which has been continuing trend considering that for this paper 280 are qualified from five-year range. That is almost five times as much as previous article collected from almost four-times wider time range. At their paper, Kulak & All also found out that Independence axiom was clearly more usually applied out of two axioms in academic papers (Kulak, Cebi & Kahraman 2010: 6710) and that crispy evaluation method was significantly more popular than fuzzy approach. In this research, this is one of interesting comparison points, that is to see if this trend has changed or if these shares still are consistent in sight of more recent publications. Out of application areas, product design was most popular and system design, software design and decision making were sharing close to equal amount of interest (Kulak, Cebi & Kahraman 2010: 6710). In the previous paper, clearly less popular topics had been manufacturing system design and other areas of application. It

is also interesting to see if there has been a change or new trend in the application areas of AD, and whether services are playing any significant role on these applications lately.

4.2 Results of SLR

In this paper, same categorization as per previous literature review of applications of Axiomatic Design by Kulak, Cebi and Kahraman (2010) has been used. Four main groups are as per Kulak & All (2010:6707) (1) type of axiom: either independent or information or both if involved in a particular paper; (2) application of Axiomatic Design principles: divided similar categories as previous paper in addition with a separate category for services, said categories being product design, system design, manufacturing system design, software design, decision making, services and others; (3) method defining applied methodology of review study, being either practical application of AD principles, integrated method where AD has been used together with another theory or theoretical development aiming to create new theories to be applied within use of AD and finally (4) type of evaluation, whether circumstances of application are defined to be crisp or fuzzy.

Following subchapters 4.2.1-4.2.7 a generic overview of couple of type-examples of each application are presented. Articles that could be defined as some sort of exception for its segment are paid more interest in following subchapter 4.3-4.7. Also, in the very same chapter, overview of three other main group is delivered: this aspect was missing from study of Kulak & All (2010) but seemed reasonable to be include in this research.

4.2.1 Product Design

Product design is a definition of a process where either completely new products are designed or design of existing products is improved. According to Suh (2001: 377), a product development cost is relatively high in comparison of its lifetime revenue. For

this reason, according to Suh (2001:377), companies developing non-competitive products are launching for failure. Logical and methodological approach of design process for products at early phase has a high importance since decisions at this phase have significant impact on overall success or failure. (Marzullo & All 2015: 56-57)

During evaluating articles of SLR, total number of 99 articles involving product development as an application of AD was discovered. Concluded number of each application can be seen in table 8. Altogether, product development was a most involved application area of AD among all reviewed papers, in total 35 % of all papers. In total, four examples of product design with AD has been reviewed below to review examples into what products and how AD has been applied in reviewed papers.

Monti, Giorgetti & Girgenti describe in their paper "An Axiomatic Design approach for a motorcycle steering damper" (2015) an Axiomatic Design-oriented design process to reach a design of a motorcycle steering damper that would overcome current disadvantages of steering damper functions that could, according to authors, decrease driver's safety and comfort under normal conditions. Authors first explain functional principles of steering damper. Principles of Axiomatic Design and more precisely independence axiom is applied to highlight problems of designs of current steering dampers: since design generally has more FRs than DPs it is coupled and therefore it cannot be ideal. Innovative design of steering damper is introduced using magneto-rheological (MR) fluid technology resulted a solution where FRs can be satisfied with independent DPs and therefore neither safety nor comfort needs to be compromised.

In their article "ADjustadesk – An Adjustable Height Desk" Foley, A.F.Símonarson, H.P. Símonarson, Ægisson & Goethe (2017) aimed to design a workshop-consistent and price-effective, mechanically adjustable work-desk. Authors followed a very traditional, systematic methodology of Axiomatic Design for product design starting from Customer Attributes and transforming them into Design Parameters, then forming a design matrix and ensure independency of FRs by either uncoupled or decoupled design. The design

authors ended up with was a hydraulic-adjustable work desk with pin-out locking screws to ensure stability, cost-effectivity and usability. Furthermore, a ready product-prototype was tested to ensure that CAs were matched as required.

Herjólfsson, Helgason, Ingvason, Pórarinsson & Foley (2018) developed a device to hold a tablet, preferably at bed in their article published with title “Design of a tablet holder with the help of Axiomatic Design”. A goal of this design process was to provide a superior design for tablet holder to be used in bed. Design process once again started from defining customer needs CAs and forming them into functional requirements FRs. These FRs were further turned into DPs by zigzagging, resulting into decoupled design matrix. Design was demonstrated with Computer Aided Design program, and strength and bending were tested to ensure safety and functionality of product. Furthermore, request to develop a model that would automatically adjust angle to a viewer’s head was proposed for future development.

4.2.2 System Design

Other than products, either physical products or services or e.g. software, there are completeness that involve multiple different parts such as software, hardware, people completing specific tasks and so on. These wholes are called systems (Suh 2001:193). System Design can be applied to many different systems such as machines, large systems, software systems, systems including software and hardware and organizations (Suh 2001:192). Below, there are three typical examples from 73 articles of this SLR where applied area of AD has been focused in to system design. Manufacturing system design is explored later at chapter 4.2.3.

Khayal & Farid (2015) researched in their papers “Axiomatic Design based volatility assessment of the Abu Dhabi healthcare labor market: Part I – theory & Part II: - case study” an application of Axiomatic Design theory for large flexible systems including methodological developments in part I whereas case study of healthcare system in Abu

Dhabi is presented at part II. In their methodology, each functional requirement was established as set of healthcare professional, and at the lowest level of DPs are individual names working on their professions. AD theory was used more for organizing data and measuring volatility in the study rather than form a functional design for the system itself.

In articles “Robust Decision making for Agile Systems Development Part 1: Exploring the paradigm & Part 2: A decomposition & Analysis” Barker & Summers (2015 a & b) present a to-step framework of delivering enterprise-based system agility into operational domain. In that point of view research can be seen as an integrated method with agility frameworks, especially with REA2CT (Robust Enterprise-based Approach to Agility in Capability Trough-life) framework, but also as a theoretical development. The first paper explores the paradigm of agility in systems and defines customer needs and preliminary design table resulting coupled design. The second paper highlights problematic points of agility design of REA2CT-framework with help of Axiomatic Design, and request changes into design to gain a better design solution.

Last example of applications of AD in System Design is an article by Smith, Shah & Cohran (2018: a) “Prevention, Early Detection, and Reversal of Type-2 Diabetes using Collective System Design”. As per head title, article is focusing of creating an early detection and reversal of chronical diseases, especially Type-2 diabetes, by using collective system design theory guided by Axiomatic Design theory. Design process itself follows guidelines of AD by decomposing FRs into DPs and analyzing design & adjusting areas that were leading into coupled design. As a result, system that rewards behavior that is preventing for Type-2 diabetes was created. Since principle of independence axiom was applied, created system can also be developed whenever new research data is available and therefore the system needs to be adjusted.

4.2.3 Manufacturing System Design

Importance of design of Manufacturing systems has been recognized since 1990s mostly because faster globalization of manufacturing industry, since design and operation of production and manufacturing system impact directly on productivity and key financial factors (Suh 2001:301). According to Suh (2001:302), the goal of manufacturing system is to "improve customer satisfaction through improvements in the quality of products, short delivery time and high labor productivity with a minimum of capital investments". Below are presented three examples of applications of Axiomatic Design theory in Manufacturing systems within papers review in this Systematic Literature review. Totally 28 of reviewed 280 articles were applying AD into Manufacturing System design.

Smulders & All (2013) published a paper "A method for indexing Axiomatic Independence applied to Reconfigurable Manufacturing Systems" (2013) where authors developed indexing method to monitor reconfiguration of Reconfigurable Manufacturing Systems. These systems are applied for their adjustability to new products, software's and processes and they thus have many benefits. One of the biggest benefit is an agility to produce new products or –modifications. In a method developed by Smulders & All (2013) this monitoring process was divided into seven stages. Method is focused on Independence Axiom and on finding all possible dependences during the monitoring process and further decoupling them. Authors also found out that developed method combines well with V-model, an optimized version of waterfall model for industrial design.

Farid (2014) discovers re-configurability further in his article "Axiomatic Design and Design Structure Matrix measures for Reconfigurability & its key characteristics in Automated Manufacturing systems". He is applying a method of re-configurability measuring process and design matrix of Axiomatic Design to build a set of composite measures of systems re-configurability's. This methodology applies use of independence axiom in a design matrix. In a re-configurability, its key characters such as modularity, customization and integrality are focused in measures.

In a paper published 2018 by Kujawa, Weber, Puik & Paetzolf (2018) another method related on Reconfigurable Manufacturing Systems is researched. “Exploring and *Adapt!* – Extending the *Adapt!* Method to Develop Reconfigurable Manufacturing Systems” – titled paper is extending *Adapt!* – method that integrates life-cycle design with early design phases of Axiomatic Design, by adding an exploring phase on the method. The development has been done for automotive industry since new models are designed years ahead of manufacturing and therefore exploring phase would, according to authors, give manufacturing a smooth start by providing opportunity to adapt in advance becoming changes.

4.2.4 Software Design

Axiomatic Design theory for Software design or Software System design has multiple benefits: according to Suh (2001:239) it is self-consistent, easy-to-change and provides interrelationship between modules. Axiomatic approach has been applied into Software Design to overcome some of the known shortcomings of software design, especially need for correcting and changing that has been consequence of non-methodological design of software (Suh 2001:242). Total number of 8 articles were focused into Software design out of reviewed 280 articles.

Woolley, Li & Tate (2013) published paper “The Application of Sequence Enumeration to the Axiomatic Design process”. The paper focused on attributes of Axiomatic Design for software engineering and evaluating one methodology of software engineering, Sequence Enumeration – technique. Focus of AD for software engineering lays on independence axiom, design matrices and decoupling coupled designs and furthermore decomposition process. In a similar detail theory of Sequence Enumeration is presented. Finally, study applies both presented theories simultaneously into a case study of designing simple watch. Generally, AD had been applied into a design process in a higher

level whereas principles of Sequence Enumeration have been applied into a more detailed level.

In a paper “Modelling collaborative product development using axiomatic design principles: application to software industry” Arsenyan & Büyüközkan (2014) are focusing on product development theory called Collaborative Product Development (CPD). They develop a Collaborative Product Development model that is based on Axiomatic Design for software industry, offering a system perspective into a model. First principles of CPD are explained, as well as methodology of AD: in an AD methodology focus lays strongly on independence axiom, mapping & decomposition and design matrices. Further, a CPD is modelled using principles of Axiomatic Design and finally developed model is tested with a case study with a software company collaboration in a process.

As a third reviewed article for Software design, a slightly different paper is selected. Two-part study of Rolli, Parretti, Citti & Rinaldi (2016 **a** & **b**) is a research that aims to improve a process of public taxation in Italy. A paper has a title of “Improvement of the compilation process of the Italian income certifications: a methodology based of the information content (Part 1) and an application of the tax model of year 2016 (Part 2)”. The goal of the study overall is to simplify the process both for government (as a collection of fiscal data) and customers as providing simpler paths of completing their tax information. Both goals are approached by designing functionalities of software used for the purpose. Paper 1 focuses on theory and on building a robust process for collecting the data by using principles of Axiomatic Design. When decomposition functional requirements, papers use functional point estimate - technique for decomposition. Paper 2 applies results presented in first article for tax year 2016 for Italian tax system. With a decomposed design authors concluded that found solution would be most cost-effective and functional software design solution.

4.2.5 Decision making

Axiomatic Design principles for Decision making are applied as a part of design process when necessary, as engineering design could be defined according to Gonçalves – Coelho & all (2007:81) as a loosely structured activity including learning processes, defining problems, decision-making and design objects representation. Interestingly since in Axiomatic Design methodology as per chapter 2 presented earlier, best solution is usually found through Independence Axiom. However, if there are multiple equally good solution from a perspective of first axiom, Information axiom is used to define which of available solutions is superior. Therefore, normally in papers presenting AD for decision making, perspective of Information Axiom is applied. Total number of 27 articles of reviewed involved principles of AD for decision making.

Cheng, Xiao, Zhang, Gu & Cai (2014) published their article "An Analytic Robust Design Optimization Methodology based on Axiomatic Design principles", where Information Axiom was introduced into a novel method to select best design with gained robust optimized models. Authors define that Analytic Robust Design methodology that they provide is useful especially when physical experiments cannot be concluded. Most significant benefits with a newly developed ARD model with a help of AD is, according to Cheng & All that it provides covariance matrix between FRs and DPs, that it provides scientific base on evaluating which of the reached solution is superior with appliance of Information Axiom and finally that its proposed method that is performed via matrix formulation is more easily computed.

An article "A fuzzy information axiom based method to determine the optimal location for a biomass power plant: A case study in Aegean Region of Turkey" Cebi, Iltahar & Atasoy (2016) present a case example of applying Information Axiom in a fuzzy (non-numeric) decision making in a case problem. Method used in the paper has been an integrated with Fuzzy sets, Analytic Hierarchy process, Opinion Aggregation method and Information Axiom. A research has been carried out in three phases, from (1) definition of criteria trough (2) evaluation to (3) output. Finally, sensitivity analysis is carried out

for reached results to ensure the decision output from earlier phases. Authors summarize that selection method can be implied different kind of location decision processes and therefore expended from biomass power plant to reach wider purposes.

Last reviewed article for AD applications for Decision making is selected an article "Extending a pessimistic-optimistic fuzzy information axiom based approach considering acceptable risk: Application in the selection of maintenance strategy" by Seiti, Hafezalkotob & Fattahi (2018). The paper aims to present a mathematical model for decision making for proper maintenance in risky situations. It applies model of Fuzzy Axiomatic Design FAD with both optimistic and pessimistic fuzzy scores. After presenting a general theory of FAD, authors propose an eight-step FAD model for decision making considering acceptable risk. Further, a proposed method is tested in rolling mill company.

4.2.6 Services

Interestingly, in earlier literature review of Cebi & All (2010), applications of Axiomatic Design into design of services was not mentioned nor researched. Although many authors such as Chen & All (2016) and Arcidiacono & All (2016) have published papers about principles of Axiomatic Design applied in services, there is no study or methodology of AD particularly for services. However, growing service sector in post-industrial economies has increased service market and demand of similar competitive edge into service sector that industrial sector has gained with design methodologies. Out of reviewed papers 9 applied principles of Axiomatic Design for services.

Bae, Moon, Park & Morrison (2013) published a paper "Axiomatic Design and implementation of service-oriented university classes: Emotions and senses" where they apply designing of University classes as services with FRs found from other service designs, using principles of Axiomatic Design. Particularly they decided to identify functional requirements that are connected to emotions and senses. Main focus of the paper is theory of education and Axiomatic Design, and defining DPs and FRs based on

that knowledge. However, once FRs and DPs are set, design matrix is formed and further developed to end up with uncoupled design. Ultimate goal of this service-oriented design was to create connection with university content and ideas that students care about and thereby improve services provided by universities.

“Application of Axiomatic Design for Project-Based learning methodology” was written by Arcidiacono, Yang, Trew, Bucciarelli (2016). Study is aiming to apply principles of Axiomatic Design on learning process of Project-Based learning in general, that according to Author is heavily based on know-how and trial-and-error basis, and specifically there Lean Six Sigma training. FRs are defined based on training goals and DPs that are currently used in the training are defined. Based on that data, authors were able to form a design matrix and notice that current design was coupled. Therefore, design vulnerabilities of training were able to be highlighted and suggestion to improve said service were made.

A final article reviewed for AD applications for services is written by Fargnoli, Haver & Sakao (2018) with a title “PSS modularization: A customer driven integrated approach”. PSS shortens from Product-Service System and stands an approach where company provides combined product-service package instead of providing products and services separately. This has been researched to lead higher customer satisfaction, according to authors. Authors use an integrated applying of QFD for PSS, AD and service blueprint tools. In their study, Fargnoli & All (2018) decided to use AD principles for mapping and decomposition of FRs and DPs whereas design matrices where formed according to QFD principles. However, after QFD procedures, also design matrix of AD was formed to ensure acceptable design in a view of independence axiom. Service blueprint methodology has been used to recognize services impact on combined product-service package. Although authors came up with a methodology to design services supporting to products, they noted that methodology should be verified in further studies since it was specifically developed for biomedical sector.

4.2.7 Other

As per study by Cebi, Kulak & Kahraman (2010) also articles reviewed for this literature review included individuals that could not be clearly categorized by application of AD principles. Therefore, a general overview of few articles from this category is equally provided along with explanation why categorization into pre-selected groups was not either possible or reasonable. Out of reviewed articles 29 were segmented as “other”.

Thompson (2013) researched in his article “A classification of procedural errors in the definition of Functional Requirements in Axiomatic Design theory” a phase, that is according to him one of most critical and difficult in AD. That being definition of Functional Requirements. Thompson defines five types of procedural errors in definition of FRs, them being (1) Mixing FRs with DPS, (2) Mixing FRs with other type of requirements, (3) Mixing FRs of the various type of stakeholders and of the artifact, (4) and finally (5) Defining negative FRs. Through the article, all five types are explained with examples and also with possible sub-categories. Thompson does not provide solution to presented procedural errors, although article is capable of rising awareness of these errors. As being very commonly formed methodological notification of AD, article was not included in any of the application categories.

Another example of a paper that is not included into any of the application categories is a paper that is focused on theory or methodology development in a general level. Such a paper is e.g. “Axiomatic Design and TRIZ: Deficiencies of their Integrated Use and Future Opportunities” written by Borgianni & Matt (2015). Article is focused on researching publications that are involving integrated use of AD and TRIZ and evaluating why despite very promising, complementary methodologies the integrated use has not evaluated more than it has by the time paper was published. Borgianni & Matt (2015) described both effectiveness of integrated use of two methodologies such as complementary of objectives and results of practical applications, and also problems of combined use of AD and TRIZ such as TRIZ ability not to solve functional coupling.

Authors concluded that despite decreasing interest of design community of integrated use of two methodologies, they still have benefits combined that should not be overlooked, such as simplifying use of Information Axiom with the help of TRIZ.

The last example of *Other* – categorized articles is "Using Extenics to describe coupled solutions in Axiomatic design" by Li, Song, Mao & Suh (2018). Paper provides a novel method of describing coupled design by using the basic concept of Extenics. Authors combine methodology of Extenics-design with Axiomatic design aiming to provide a tool for decoupling possible coupled design during AD process. Finally, a paper proposes three different directions for describing coupling problems of AD with a help of Extenics.

4.3 Analysis

With completely 280 papers passed a final criteria of Systematic Literature Review approach, articles were divided into four main categories as per described in chapter 4.1 according to benchmarked study by Kulak, Cebi & Kahraman (2010). These categories were (1) applied axiom, (2) application of Axiomatic Design, (3) method and (4) type of evaluation. Numeric values can be seen in table 8 below. It is noticeable, that some papers might have more than one option of each category, e.g. if both Independence and Information axioms had been clearly applied for a study. As well, it is possible for a paper not to have any categorization at all if for example it has focused on theoretical development in the area of AD where neither of the axioms clearly are involved, such as decomposition without design matrix. Below in table 8 there is a numeric conclusion of the results of SLR and figure 11 summarizing number of articles published by year. As well in figure 11 there is a graph illustration of published articles by year. The whole SLR table is presented at appendix I, and all articles are listed in references. Graphs of the results are presented later on chapter 5 to compare results with previous review.

As seen in table 8, vast majority of articles is applying first of the two axioms. This is not necessarily only because of nature of Axiomatic Design. As explained before,

Independence Axiom should be fulfilled first and then if there are equally good solutions, Information axiom is applied to find best of said solutions. But this could be also because information content of design is more challenging to calculate and may not even be cost-effective in all cases as preciously explained. Furthermore, interestingly most of articles applying Information axiom were dealing either with application as a decision making or theoretical development, as can be seen from whole data from appendix I. Although there were 16 articles where both Axioms were involved, they were mostly considering a theoretical development such as Oh (2013), Puik & Ceglarek (2014) or Mabrok, Efatmaneshnik & Ryan (2017). Although papers where application of Axiomatic Design has been applied with use of both axioms such as Girgenti & All (2014) or Rolli & All (2016 a & b), a clear application of AD where first Independence Axiom is applied to find a best solution possible, and then Information Axiom applied since first axiom resulted multiple equally good solutions is still missing. It seems based on this SLR that authors are focusing either of the two main axioms in their research.

Table 8. concluded data of Systematic Literature Review

Axiom	Independence	210
	Information	64
Applica-tion area	Product	99
	System	73
	Manufacturing system	28
	Software	8
	Decision making	27
	Services	9
	Other	29
Method	Application of AD	153
	Integrated method	68
	Theoretical development	54
Evaluation	Crisp	237
	Fuzzy	39

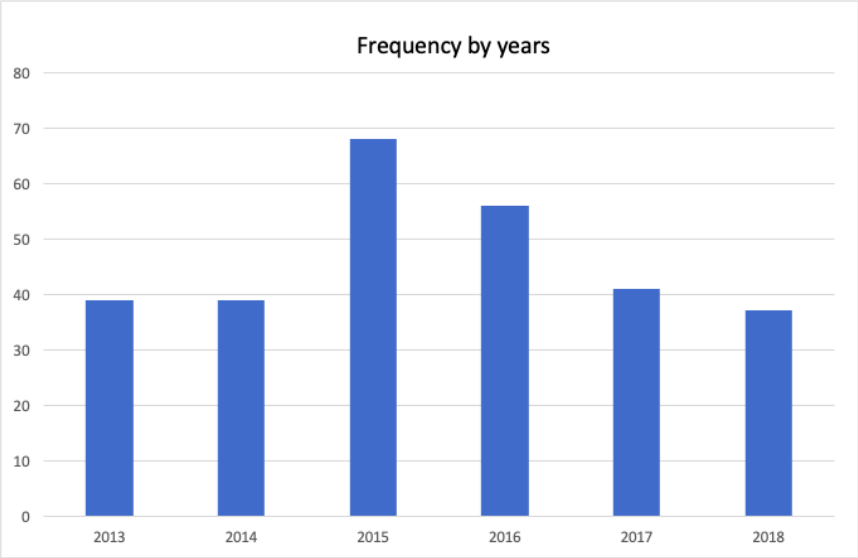


Figure 11: Articles by publishing year

Other remarks are also made by application area of AD. Clearly AD for software and service design is least researched by academic papers, resulting 8 papers involving AD for software design and 9 papers involving AD for service design. Later application area and relatively low interest on that academically could be resulted by the history of AD as an engineering and industrial-related methodology, but since authors like Suh (2001: 241) and Chen (1998:243-244) highlight benefits of AD for software design, low number of articles from this application area is an interesting fact and arises possible need of future research. Vast majority of SLR's papers have been using application of AD as a research method with total 153 papers, whereas integrated method and theoretical development are sharing fairly equal amount of 68 papers of integrated method and 54 papers of theoretical development.

A publishing frequency during period selected for SLR seems constant excluding a small peak in a number of papers published in 2015 (68) and 2016 (56) as per figure 11 above, otherwise volatility of number of papers published is fairly low, only 4 varying between 37 (2018) and 41 (2017) papers per year. From 2013 till 2016 there has been increasing number of articles including appliance of Information axiom, from 7 up to 16 articles, but latest year selected for study this number has sink back to 8 articles. This would also

be interesting to research in future is this continuing trend or is Information Axiom researched more in future papers.

Attached a graph showing concluded data by year of current SLR

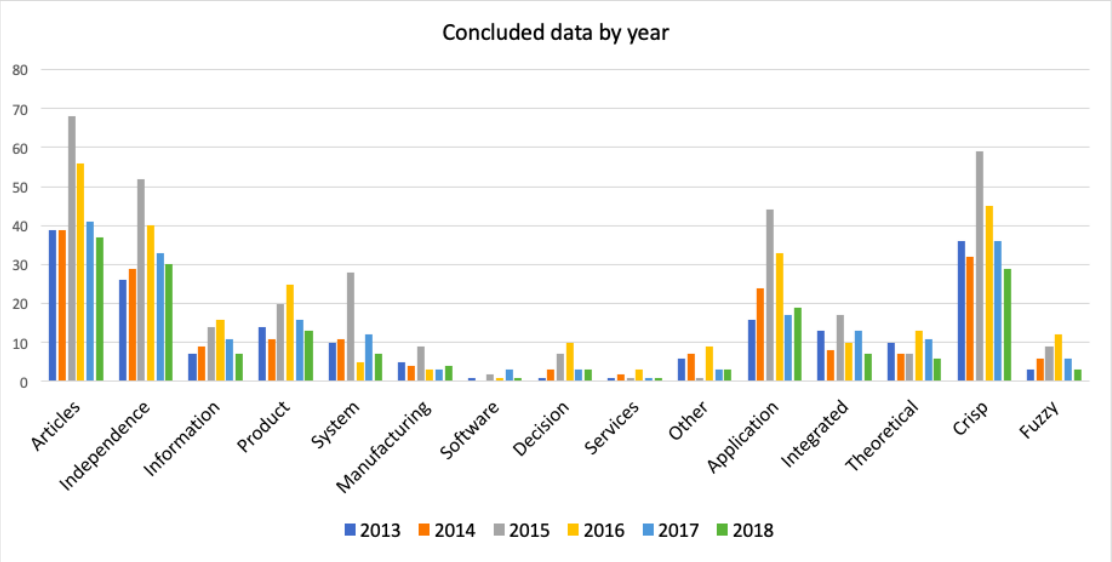


Figure 12: Concluded data by year

From there a correlation between appliance of Information Axiom and evaluation as a "Fuzzy" can be clearly seen as per year 2016. This was since several articles such as Khandekar & Chakraborty (2016), Kir & Yazgan (2016) and Arsenyan & Büyüközkan (2016) are researching fuzzy Axiomatic Design in their papers, which is a theory involving use of Information axiom. However, in 2017 and 2018 number of these kind of researches has decreased, 2017 involving only 8 papers with fuzzy evaluation whereas 2018 had 6 papers with fuzzy evaluation.

4.4 Comparison with benchmark study

As mentioned in introduction and chapter 3.3, this study has been benchmarked with a previous literature review of Applications of axiomatic design written by Cebi, Kulak & Kahraman (2010) reviewing articles published between 1990 and 2009. Due to early years of academic research of Axiomatic Design authors of previous paper were able to establish a lot wider time-window, collecting manageable amount of papers with total number of 63 publications. Within selected window of past five years when starting this research, between 2013-2018 total number of articles that were accepted through ought selected SLR criteria was 280 papers as per appendix I, and as discussed in chapter 5 Limitations, not necessarily all published papers of the matter have been selected into this study.

In a previous study by Cebi, Kulak & Kahraman (2010) cumulative number of publications was relatively low, between 1-3 papers per year between1990-2001 as per figure 13 below. After 2001 a number of papers per year has significantly risen. Authors did not analyze reasons for this change in their paper, one possible factor might have been book by Nam P. Suh “Axiomatic Design – advances and applications” published in 2001 that might have effected increasing interest in topic on that time. Compared to SLR carried out, there is no significant trends as per figure 11 except slight peak in years 2015-2016, which is mainly due higher number of articles reviewed in International Conferences of Axiomatic Design during those years.

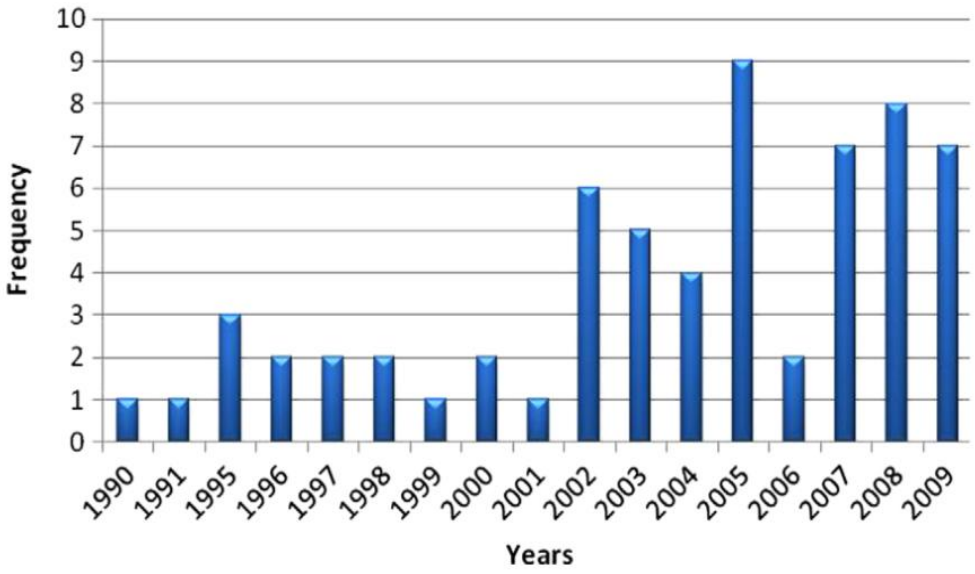


Figure 13: Publishing frequency on articles reviewed by Cebi, Kulak & Kahraman (2010)

Compared to previous study, there has no significant changes in applied axioms or evaluation as presented below in figures 14, 15, 16,& 1: for both share of Information Axiom and fuzzy evaluation have slightly reduced within papers viewed for current Systematic Literature Review. There has been slight variance within different years however in a share of these categories, as per presented in figure 13 above. However, no graphs are presented to view such a data from previous study. Applied axiom and type of evaluation are previewed below as a pie chart. However, previous study did not present share of method used in a paper as a pie chart. This share regarding current SLR is presented below in figure 18, but unfortunately there is no comparison as per mentioned before from previous study.

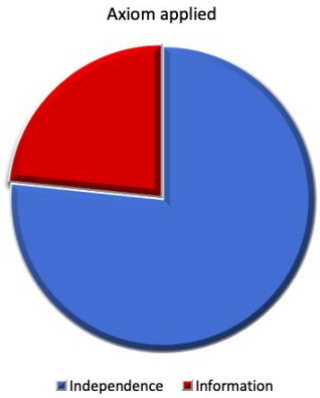


Figure 14. Axiom applied

Figure 15. Axiom applied by Kulak & All (2010)

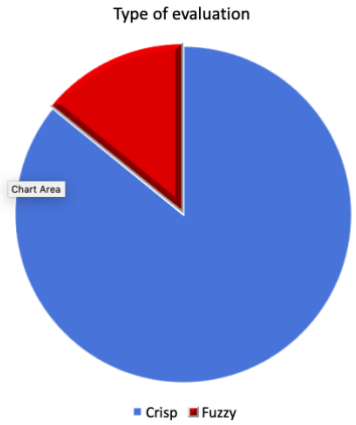


Figure 16. Type of evaluation

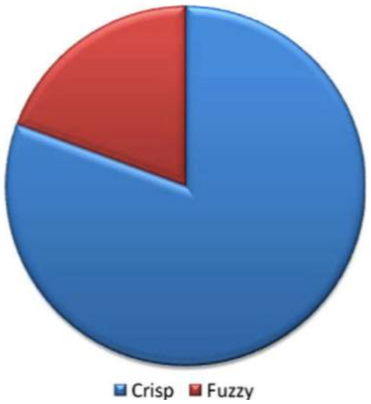


Figure 17. Type of evaluation by Kulak & All (2010)

The axiom applied as per figure 14 & 15 is not surprising, due to as concluded before that Independence Axiom should be satisfied first in AD and after that, if there are multiple equally good solutions, information axiom should be applied to find the best solution available. As mentioned per chapter 4.2.5, most of papers involving Information Axiom are focused either on decision making or theoretical development on decision making / Information axiom. However, type of evaluation is more interesting since Fuzzy Axiomatic Design can be seen as an individual part of Axiomatic Design theory. It might have been chosen originally to be part of evaluation criteria since authors of previous study have not only been working with Fuzzy AD theory, but it has even been developed by Kulak & Kahraman (2005). It might be reasonable to reevaluate in future studies if this is significant information to be evaluated in SLRs.

Al contrary to applied axiom and evaluation method, application of Axiomatic Design in previous review and current review have some interesting differences as presented in graph below. Product design is clearly dominant in both reviews, but system design has in this SLR clearly more significant role than before. Also share of articles including applications for decision making has reduced in more recent review, as has number of articles involving software design. A pie of “others” has remained more or less similar, as has manufacturing system design. It might be relevant to question if decision making developments have played significant role of interest paid in this sector during previous review.

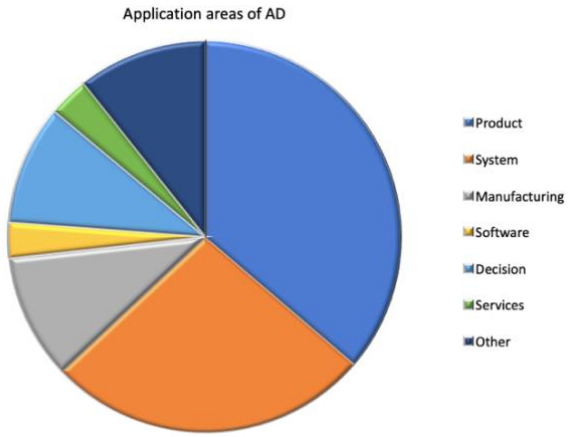


Figure 18. Application area of AD

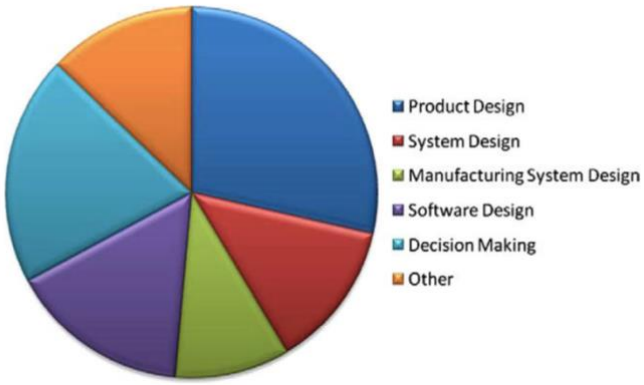


Figure 19. Application area of AD by Kulak & All (2010)

Furthermore, in previous article there was no graph nor discussion with shares of methodology of reviewed articles. Below, in figure 20 there is a presented share of methodology of current review, having a share of 55% of all articles. As per presented, application of AD is clearly most popular methodology in scientific paper. Interestingly applications vary a lot from developing relatively simple mechanical product designs such as adjustable table (Foley,A;F.Símonarson, H.P;Símonarson, Ægisson & Goethe 2017), into complex system designs such as custom-software for processing the stress-corrosion experimental data (Girgenti, Giorgetti, Citti & Romanelli 2015). Integrated method had a second-largest share of methodology, totally 25 % of articles and theoretical development had a share of 20% of all articles viewed.

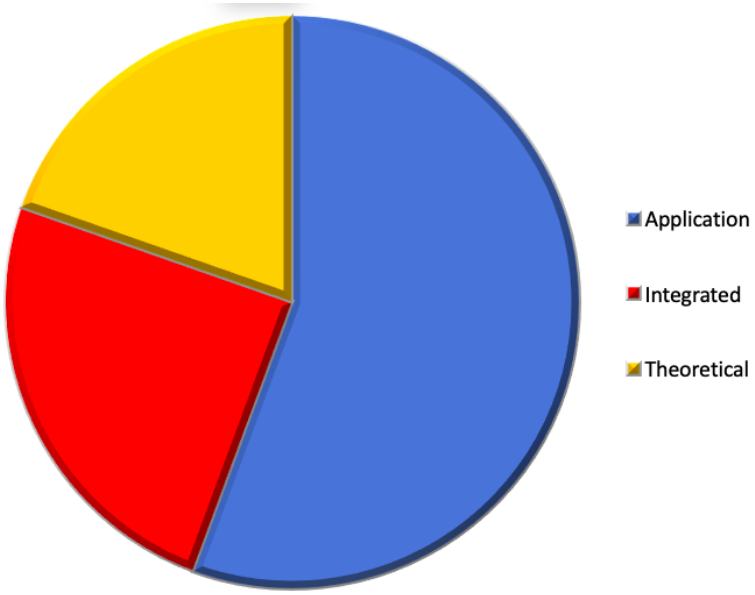


Figure 20 Applied method

In the next sub-chapter 4.6 some of the remarks made while categorizing articles with methodology, axiom and type of evaluation are presented to complete analyze and result as per presented in chapter 4.2 and 4.3,

4.5 Axiom applied, methodology and evaluation method

Previous literature review by Cebi, Kulak & Kahraman (2010) did evaluate and refer all the reviewed papers by application of Axiomatic Design as performed in chapter 4.2 with three examples of each category. Following results of SLR are discussed in a view of these categorizations overlooked in chapter 4.2, in the other words from view of Axiom applied, Methodology and Evaluation method.

As an applied axiom, Independence axiom was in general way more involved than later of the axioms, Information axiom. Most typical application of Independence axiom used by several papers such as Kreuzer, Nitsche & Kantola (2014); Bragason, Porsteinsson, Karlsson, Grosse & Foley (2015) and Delaš, Škec & Štorga (2018), is to use its principles to evaluate design matrix and ensure uncoupled or decoupled design. However, there are some counter-examples where design matrix is not a primarily used or might have been used to aim "bad design", referring a coupled design. For example, Nakao (2016) notice in his paper that even though uncoupled or decoupled design is superior to coupled design, it can be too easily imitated by competitors and thus more complicated design solutions might be preferable. As discussed previously, most article that are applying use of information axiom are focused on decision making. Out of evaluations method-category, Fuzzy Axiomatic Design relays strongly in a use of Information axiom.

Most popular methodology by over 50% of evaluated papers were application of AD in different design or developing processes. However, there is a significant share of articles focusing on either integrated method, theoretical development or combination of both of them. There are several methodologies integrated with Axiomatic Design in reviewed papers, few of the most popular were Quality Function Deployment QFD as per Cavallini, Costanzo, Citti & Ciorgetti (2013) and Gilbert, Omar & Farid (2014), TRIZ as per Borgianni & Matt (2014) and Analytic Hierarchy Process as per Chakraborty, Mondal & Mukherjee (2017).

4.6 Papers with inconsistencies on selected methodology

Final part of discussion will include some notes and discoveries of papers that were either challenging or even inconsistent to categorize according to selected criteria. Alongside with explaining and referring these articles, some notes are made that are transformed into chapter 5.3 Recommendations for future research.

One of the largest subject that could possible been separated into own application/declaration area of Axiomatic Design in reviewed papers was teaching Axiomatic Design and axiomatic design in education. Out of explored papers there were 10 which were implying either teaching or learning of AD, or AD application related on teaching or learning. For reviewing these articles, they have divided into two groups: papers about teaching AD and papers about application of AD into teaching and/or learning. There are totally two articles regarding teaching AD. Liu & Lu (2013) published a paper "Lessons learned from teaching Axiomatic Design in engineering design courses" where they concluded some challenges or difficulties that students were facing when learning AD and proposed certain theoretical foundations and teaching methods to overcome these difficulties. Nakao & Iino (2018) write in their article "Students List FRs Chronologically and DPs Spatially, and Need to Integrate FRs Functionally and DPs Physically" about a practical method they use teaching AD, where decomposition process is handed to students before teaching principles of AD and then a proper zigzagging method is applied to first improve design charts and further to apply Independence Axiom for improved design.

Asides for mentioned two articles, there were eight articles regarding applying principles of AD into teaching of some sort. Betasolo (2016) applied it to identify best learning methodology; Benavides & Rodríguez (2013 **b**) researched a vacuum cleaner as a case study to teach conceptual design and quite similarly Park (2014) published paper about teaching conceptual design using AD; Slâtineau, Dodun, Seghedin, Coteatâ, Besliu & Gherman (2014) write about applying AD principles when teaching Manufacturing

technology design; Llego-Betasolo (2014 a & b) created in their two-part study AD model to asset influences affecting students learning in two engineering courses to improve students' performance; Dodun, Panaite, Seghedin, Nagit, Dusa, Nestian & Slatineanu (2015) provide analyze of Moodle – e-learning platform aiming to provide clearer definition of customer needs and tools to satisfy them by applying AD into analyzing-process; Arcidiacono, Yang, Trew, Bucciarelli (2016) suggest applying AD into Project-Based learning methodology that is normally run by know-how and trial-based-errors, and finally Bae, Moon, Park & Morrison (2013) explore how applying AD into designing University classes as a services by applying CRs of other services might improve their design by including emotions and senses into design of University classes.

Although examples mentioned above vary on application area of AD since there are service-oriented applications as well as software-oriented articles (although arguably Moodle could be seen as a system including both software and services), this is providing interesting field for possible future search: to see how AD has been applied for learning and teaching methodologies and is there a possibility of improve teaching of AD as per previous chapter by designing teaching or learning with help of AD.

Aside from articles dealing with learning, teaching or education, other segment worth of individual attention are papers that have a critical view of Axiomatic Design theory. Vast majority of publications had limitations-chapter in their study explaining what is particularly limiting for that paper. However, there are few studies approaching either part of AD theory or whole procedure critically, evaluating possible problem and suggesting a solution, usually as a part of theoretical development.

Thompson (2013) classifies in his paper procedural errors of defining Functional Requirements in Axiomatic Design, involving not only errors made by beginners but also ones made by experts of the field. As well, Thompson is asking in his other paper (2014) where is "Why" in Axiomatic Design, highlighting the issue that motivation, goals and values of design process are traditionally not involved in AD theory and suggest where

and how they should be involved. Vossebeld, Foley & Puik (2018) are focusing on mapping Customer needs into Functional requirements and the fact that this aspect is often overlooked whereas Sharma & Cudney (2015) research applications and limitations of AD complexity in Quality engineering, providing bounded solution for complexity for a normal distribution.

4.7 Answers to the research questions

Based on results presented below, relevant data has been collected and processed to provide answers for research questions presented earlier in introduction and chapter 3. To remind the research questions, RQ1 asked if there is a significant change in applications of AD in 2013-2018 compared with previous literature review, and this was further decomposed in RQ1.1-1.3 in view of axiom applied, applications and what share service design is having in applications of Axiomatic Design.

To start from decomposed research questions, RQ1.1 asked if there is a significant change in proportions of axioms. As can be seem from figures 15 and 16 presented above, there is virtually no change in proportions of axioms within academic publications. Furthermore, RQ1.2 questioned is there a change of proportions of applications in AD within academic publications. Here as per figures 19 and 20, some changes can be discovered. A portion of product design remains as one having a biggest share of applications. However, proportion of system design has risen from previous literature review significantly and software design has reduced. This arises a question of the impact the categorization criteria might have on the results since software design can be seen as a specific area of system design.

Finally, proportion of services as per RQ1.3 is relatively small in applications of AD as per figure 19 sharing almost equal proportion with software design. Both of these

applications would be recommended for future research to find out if there is a specific reason why the proportions of the two are as low as presented.

5 Discussion

In this chapter limitations of Systematic Literature Review performed earlier are discussed and highlighted. Limitations are focused according to following two subchapters in a 5.1 scope and exclusion criteria and 5.2 categorization. In final subchapter 5.3 some recommendations for future research are provided. It is also noticeable that even though comparison has been done with previous systematic literature review by Cebi, Kulak & Kahraman (2010), benchmarking with other literature reviews of Axiomatic Design has not carried out. There are two within explored papers, by Marchesi, Kim & Matt (2013) that focuses on AD approach on design of Architectural systems and by Sadeghi, Houshmand & Valilai (2017) that focuses on AD theory in design for human safety in Manufacturing Systems

5.1 Scope and exclusion criteria

As explained in chapter 3, used search terms were applied from previous study by Kulak & All (2010). Even though these terms are covering most obvious and important aspects of Axiomatic Design, it is reasonable to consider for future researches whether extending amount of search terms e.g. into decomposition and zigzagging would be reasonable. Also, this study was strongly limited by the time available and thereby into search criteria subject limitation of “Axiomatic Design” was set. Thereby some of possible significant results might have been excluded, although that seems unlikely.

It is noticeable that only databases included into FINNA article search of University of Vaasa as per figure 9 had been included. There is another way to expand study by search possible other open source article databases such as Google Scholar. Also, depending if researcher has access to a library with wide technical publications, there might be books or articles not available online that could be included: from databases of University of Vaasa no books published between year window selected was discovered. It is also noticeable that especially most recent publications are usually if not available, at least

mentioned online-databases. A considerable limitation benchmarking with previous study by Kulak & all (2010) is that a gap between 2010-2012 exist that is not included in neither previous nor this literature review.

A final note for exclusion criteria is lingual. Only articles published in English were included into this review for practical reasons. However only one paper published in Spanish was excluded for that reason.

5.2 Categorization

As discussed before in chapter 4, a categorization of results might be needed to consider in future studies. Evaluation method does not seem reasonable to be included in categorization criteria for other reason than to gain comparability with previous study. Although papers including Fuzzy Axiomatic Design have their own particular methodology, for example integrated method with Analytic Hierarchy process seems as reasonable or –unreasonable categorization as evaluation method. Furthermore, within years not included into either of the literature reviews (2010-2012;2019) it would be interesting to make a conclusion of literature reviews and view if there is a trend on any of the categorizations.

Further notes on categorization are made on next chapter 5.3 Future studies, but it is remarkable to note that since number of articles published has significantly increased from era when Cebi & All performed their review, limitations are not recommended but necessary to effectively perform a Systematic Literature Review. However, these limitations should be critically considered so that significant results will not be excluded from a review.

5.3 Reliability and generalizability

Before exploring recommendations for future research, it is reasonable to critically evaluate conducted research. For the reliability of the research, there are few key things that need to be considered. These things are objectivity of categorization criteria, databases and comparability and, finally, research decision evaluations.

Even though this research was conducted as per described in chapter 3 according to the principles of Systematic Literature Review, there is an amount of possible subjectivity that needs to be discussed. In case of this particular research, it is mostly related to the categorization criteria. In previous study by Kulak, Cebi & Kahraman (2010) an evaluation criteria for different categories was not defined. Neither was it specified at the beginning of this research. That leaves a grey area where a researcher needs to decide if an article should be included into one category based on e.g. theoretical mentions of Information axiom but not applying this principle into a study. For example, these articles were not included into “Information Axiom” during evaluation of this research. However, this subjectivity is nearly impossible to avoid at some level since there is always an area that questions researcher about evaluations of this kind.

Furthermore, database used for this research was FINNA-article database of scientific articles that University of Vaasa has access into. Since previous study was carried out by authors working in different university, a database they used was different even though it had access to at least partially same databases such as ScienceDirect and Taylor & Francis were used also by previous authors (Kulak & All 2010:6716). This arises a question if selected databases might cause possible bias into a research. However, since authors of previous review have publications in a ICAD-conferences, that was the primary source of articles, a comparability of some level is presumably existing.

Finally, since this research has been conducted by one person with a limited supervision of University personnel, evaluation choices, inclusion/exclusion choices etc. are arguably

more subjective than when such a research has been carried out as a team, as per previous study. The effect of this is unclear, but the fact that all the decision related e.g. to included and excluded articles and categorization has been carried out by single person might have impact on the study.

Based on this research and comparison with previous research, some generalizations can be made of research carried out related to Axiomatic Design. First, more usually first axiom of the two is applied into design process. If second axiom is applied, usually it is related to decision making within a design process. Furthermore, a crisp evaluation method is significantly more popular within publications than fuzzy evaluation. Finally, a most used application of AD within academic publication seems to continue being application for product design, while some areas such as Software Design keep staying relatively low.

5.4 Recommendations for future research

For future research, as mentioned in chapter 6.2, a study of lot narrower time range but wider search and inclusion criteria is recommended. As well as conclusive study, not necessarily very detailed in article-level but one that is concluding data from Systematic Literature Reviews and filling gaps that exists due to selected time ranges. For that review, analyzes of possible trends in applications areas, use of axioms or method is recommendable.

Another recommendation for future research is to perform a systematic review of different categories explained in previous study and this review. For example, a Systematic literature review of Application of Axiomatic Design in Software Design, or SLR of applications of AD with QFD in scientific publications. Further, a different review of service design and applications of AD in that area should be performed. Latest kind of review could be performed in much more detail since amount of results (depending naturally on evaluation and –inclusion criteria) would be significantly lower.

6 CONCLUSION

In this research, a Systematic Literature Review of academic publications related on Axiomatic Design and published between 2013-2018 was carried out. Findings of the research were compared and contrasted with previous literature review of publications between 1990-2009 by Kulak, Cebi & Kahraman (2010). Research questions for comparison and contrasting were formed as following

RQ1: Has there been a significant change in application of Axiomatic Design in past five years compared to the literature review by Cebi, Kulak & Kahraman (2010) ?

RQ1.1: Has there been change in proportion in use of information / independence axioms?

RQ1.2: Has there been significant change of applications of Axiomatic Design?

RQ1.3: What is proportion of services in applications of Axiomatic Design within research range?

As a conclusion, as per chapter 4.7, following findings are made during the research. In use of axioms, virtually no significant change exists in comparison of previous study by Kulak & All (2010). In application of Axiomatic Design, most significant changes have happened with share of applications for Software design that has reduced significantly, and with share of system design that has on contrary grown quite significantly since last research. As a proportion of applications for services, it can be concluded to be very small share having 9 articles, but still e.g. larger share than software design which had only 8 of evaluated 280 papers.

Based on findings presented in this research and limitations discussed in chapter 5 few conclusive remarks are made. First of all, a conclusive and supplementing study covering publications from years 2010-2012 and concluding these with both this study and previous study is highly recommended to create a bigger picture. Furthermore, categorizing criteria and its evaluation should be specified in more detail in future

studies to ensure unbiased and comparable results. Furthermore, questions arisen from changes in proportion of application of AD, e.g. for software or service design, are recommended to be researched. Is this due to researcher interests or university structures (e.g. little co-operation between software engineering and researchers focusing on AD), or are there simple better methods that are applied for designing software and services?

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Appendix I: Results of Systematic Literature Review

		Axiom		**Application area**						**Method**			**Evaluation**	
Author(s)	**Year**	Indep.	Infor.	Product design	System design	Manufacturing system design	Software design	Decision making	Services	Other	Application of AD	Integrated method	Theoretical development	Crisp	Fuzzy
Slâtineanu, Gherman, Dodun, Coteatâ, Besliu & Seghedin	2013			x								x		x	
Khayal & Farid a)	2013				x								x	x	
Khayal & Farid b)	2013				x						x			x	
Hao, Arenas, Kantola & Wu	2013	x								x		x		x	
Bae, Moon, Park & Morrison	2013	x							x		x			x	
Oh	2013	x	x	x									x	x	
Benavides & Rodríguez a)	2013	x										x		x	
Cavique, Conçalves-Coelho & Mourão	2013		x					x			x				x
Cavallini, Costanzo, Citti & Ciorgetti	2013		x							x		x		x	
Marques, Requeijo, Saraiva & Guerreiro b)	2013	x			x						x			x	
Matt & Raunch	2013	x			x						x			x	
Marques, Requeijo, Saraiva & Guerreiro a)	2013	x								x			x	x	
Ouellet & Vadean	2013	x		x							x			x	
Liu & Lu	2013	x	x							x			x	x	
Thompson	2013	x								x			x	x	
Nakao, Tsuchiya, Kusaka & Iino	2013	x			x						x			x	
Pallaver & Do	2013		x	x									x	x	
Sadeghi, Tricot, Mahieu & Al-Bassit a)	2013	x		x								x		x	
Sadeghi, Tricot, Mahieu & Al-Bassit b)	2013	x			x							x		x	
Bacam, Farid & Tsai	2013	x				x					x			x	
Gilbert, Farid & Omar	2013	x			x						x			x	
Marchesi, Kim & Matt	2013									x			x	x	
Espindha-Cruz, Mourão, Conçalves-Coellho & Grilo	2013	x			x						x			x	
Ferreira, Cabral & Saraiva	2013			x							x			x	
Cochran & Barnes	2013			x								x		x	
Puik, Gerritsen, Smulders & Huijgevoort	2013	x				x						x		x	
Woodley, Li & Tate	2013	x					x					x		x	

Acridiacono & Brown	2013					x						x		x	
Madura & Brown	2013			x							x			x	
Andemeskel	2013	x				x						x		x	
Benavides & Rodríguez b)	2013	x		x							x			x	
Dodun, Dusa, Seghedin & Slâtineau	2014	x		x							x			x	
Thompson	2014									x			x	x	
Nakao, Nakagawa, Iino	2014									x			x		
Rikihisa & Nakao	2014	x			x						x			x	
Marchesi, Matt, Fernandez, Kim	2014	x		x							x			x	
Kreuzer, Nitsche & Kantola	2014	x		x							x			x	
Slâtineau, Dodun, Seghedin, Coteatâ, Besliu & Gherman	2014	x				x					x			x	
Farid	2014	x				x						x		x	
Puik & Ceglarek	2014	x	x							x			x	x	
Girgenti, Giorgetti, Monti & Citti a)	2014	x	x	x							x			x	
Gilbert, Omar & Farid	2014	x		x								x		x	
Cavique, Conçalves-Coelho, Fardinho & Mourão	2014	x								x	x			x	
Henriques, Conçalves-Coelho, Requeijo & Mourão	2014	x								x		x		x	
Espadinha-Cruz,Mourão, Conçalves-Coelho & Grilo	2014	x			x						x			x	
Llego-Betasolo a)	2014								x		x			x	
Llego-Betasolo b)	2014								x		x			x	
Puik & Ceglarek	2014	x	x										x	x	
Marques, Saraiva, Requeijo & Guerreiro	2014				x							x			
Benavides & Pastor	2014	x		x							x			x	
Rodriquez & Benavides	2014							x			x			x	
Llego-Betasolo, Hallu & Kubul	2014	x			x						x			x	
Brown	2014	x				x							x	x	
Farid & Ribeiro	2014	x			x						x			x	
Girgenti, Giorgetti, Monti & Citti b)	2014	x		x							x			x	
Lee & Kim	2014	x			x						x			x	
Thompson & Foley	2014	x			x						x			x	
Bathurst & Kim	2014	x		x							x			x	
Kudzal, Zhang & Lagassey	2014	x				x					x			x	
Borgianni & Matt	2015									x		x		x	
Conçalves-Coelho, Fradinho, Gabriel-Santos, Cavique & Mourão	2015		x										x	x	
Zhu, Liu, Chen & Lu	2015	x		x									x	x	
Puik & Ceglarek	2015			x								x		x	

Flores, Conçalves-Coelho, Mourão & Cavique	2015	x		x							x		x	
Henley	2015				x					x			x	
Rizzuti	2015		x		x						x		x	
Barker & Summers a)	2015	x			x						x		x	
Barker & Summers b)	2015	x			x						x		x	
Marzullo, Gironimo, Lanzotti, Mazzone & Mozzillo	2015	x			x					x			x	
Moubachir & Bouami	2015	x			x						x		x	
Mollajan &Houshmand a)	2015	x				x						x	x	
Mollajan &Houshmand b)	2015	x				x						x	x	
Holzner, Rauch, Russo Spena & Matt	2015	x				x				x			x	
Modrak & Bednar	2015	x				x					x		x	
Weber, Föster, Kößler & Paetzold	2015	x				x				x			x	
Espadinha-Cruz, Conçalves-Coelho, Mourão & Grilo	2015	x			x						x		x	
Arcidiacono, Girogetti & Pugliese	2015	x			x					x			x	
Rauch, Dallasega & Matt	2015	x		x							x		x	
Rinaldi, Parretti, Bartolini Salimbeni & Citti	2015	x						x		x			x	
Sheikh, Abbasi, Talaei & Tahmasbi	2015	x			x					x			x	
Bragason, Porsteinsson, Karlsson, Grosse & Foley	2015	x		x						x			x	
Arcidiacono & Placidoli	2015	x		x						x			x	
Spencer & Cochran	2015	x			x					x			x	
Monti., Giorgetti & Girgenti	2015	x		x						x			x	
Sölvason & Foley	2015	x		x						x			x	
Girgenti, Giorgetti, Anselmi & Scatena	2015	x	x		x					x			x	
Jónsson, Gargarsson, Pétursson, Hlynsson & Foley	2015	x		x						x			x	
Dusa, Novac, Purice, Dodun & Slatineanu	2015	x			x					x			x	
Barbieri & Campatelli	2015		x		x						x		x	
Rodriguez, Morales & Benavides	2015	x	x	x						x			x	
Cavique, Flores, Amado, Conçalves-Coelho, Mourão	2015	x			x					x			x	
Marchesi & Ferrarato	2015	x		x						x			x	
Gabriel-Santos, Conçalves-Coelho, Santos, Fradinho & Mourão	2015	x				x				x			x	
Nakao, Takahashi, Nagato & Iino	2015	x			x					x			x	
Campatelli, Sallesi & Scippa	2015	x		x						x			x	
Thompson & Mischkot	2015			x							x		x	
Thompson & Clemmensen	2015	x		x						x			x	
Fouladi & Abedian	2015	x			x							x	x	
Dodun, Panaite, Seghedin, Nagit, Dusa, Nestian & Slatineanu	2015	x			x					x			x	

Girgenti, Giorgetti, Citti & Romanelli	2015	x					x				x			x	
Rolli, Giorgetti & Citti	2015	x							x		x			x	
Tarenskeen, Bakker & Joosten	2015	x			x						x			x	
Thomas & Mantri a)	2015	x			x							x		x	
Thomas & Mantri b)	2015	x			x							x		x	
Lu, Feng, Zheng & Tan	2016	x		x								x		x	
Cheng, Qiu & Xiao	2016	x		x							x			x	
Xiao & Cheng	2016	x		x									x	x	
Behrouz & Fathollah	2016	x	x		x						x			x	
Girgenti, Pacifici, Ciappi & Giorgetti	2016		x	x							x			x	
Fradinho, Mourão, Gabriel-Santos & Conçalves-Coelho a)	2016	x								x	x			x	
Chen, Liu & Xie a)	2016									x			x	x	
Liu, Chen & Xie b)	2016												x	x	
Arcidiacono, Yang, Trew, Bucciarelli	2016	x							x		x			x	
Foith-Föster, Wiedenmann, Seichter & Bauernhansl	2016		x							x				x	
Guls, Bjarnason, Pétursson, Einarsson & Foley	2016	x		x							x			x	
Rauch, Matt & Dallasega	2016	x	x			x					x			x	
Henley & Brown	2016							x			x			x	
Oliveira, L.E.S, Alvares & A.J	2016	x			x						x			x	
Jin, Shi, Hong, Zhang & Yuan	2016	x		x							x			x	
Jia, Li, Wei, Chen, Wang & Yuan	2016	x		x							x			x	
Erlingsson, Hreimsson, Pálsson, Hjálmarsson & Foley	2016	x		x							x			x	
Betasolo & Smith	2016	x		x							x			x	
Zhu, S.He, D.He & Liu	2016	x		x							x			x	
Betasolo	2016	x						x			x			x	
Hou, Quin, Li & Liu	2016	x		x								x		x	x
Calvique, Fradinho, Mourão, &Conçalves-Coelho	2016	x		x							x			x	
Iino & Nakao	2016	x		x								x		x	
Foley, Puik & Cochran	2016	x								x			x	x	x
Liu & Li	2016	x		x							x			x	
Fradinho, Mourão, Gabriel-Santos & Conçalves-Coelho b)	2016		x							x			x	x	
Zhu, Lou, He & Liu	2016	x		x							x			x	
Borgianni & Matt	2016									x		x		x	
Puik, Foley & Ceglarek	2016		x	x									x	x	
Rolli, Giorgetti, Citti & Rinaldi a)	2016	x	x						x		x			x	
Rolli, Giorgetti, Citti & Rinaldi b)	2016	x	x						x		x			x	

Lu & Liu	2016	x		x									x	x	
Ashtiany & Alipour	2016	x		x								x		x	
Brown & Henley	2016	x		x									x	x	
Qu, Feng, Gao & Tan	2016	x		x							x			x	
Gerhard & Foley	2016	x		x							x			x	
Gu, He & Han	2016		x			x								x	
Shao, Lu, Zeng & Xu	2016	x		x								x		x	
Nakao	2016	x		x									x	x	
Ómarsdóttir, Ólafsson & Foley	2016	x		x			x				x			x	
Zhu, Zou, Lou & He	2016	x		x							x			x	
Gabriel-Santos, Rolla, Martinho, Fradinho, Conçalves-Coelho & Mourão	2016	x		x							x		x		
Nakao & Iino	2017	x						x			x			x	
Foley,A.F.Símonarson, H.P.Símonarson, Ægisson & Goethe	2017	x		x							x			x	
Iino, Arruti & Nakao	2017	x		x							x			x	
Fradinho, Cavique, Gabriel-Santos, Mourão & Conçalves-Coelho a)	2017		x							x			x	x	
Rolli, Parretto, Citti & Rinaldi	2017	x					x				x			x	
Tarenskeen & Bakker	2017	x			x						x			x	
Puik, Duijn & Ceglarek	2017	x		x									x	x	
Calvique, Fradingo, Gabriel-Santos, Conçalves-Coelho & Mourão b)	2017	x								x			x	x	
Foley, Sigurosson, Gunnarsson & Olafsson	2017	x		x							x			x	
Foley, Puik & Cochran	2017	x		x									x	x	
Pacifici, Parretti, Girgenti & Citti	2017	x					x				x			x	
Disa, Purice, Nagit, Dodun, Ritanu & Slatineau	2017	x								x	x			x	
Stäbler, Weber & Paetzold	2017	x			x							x		x	
Foley, Omelianov, Koziel & Bekasiewicz	2017	x		x							x			x	
Egger, Rauch, Matt & Brown	2017	x			x						x			x	
Rolli, Parretti, Citti & Rinaldi	2017	x					x				x			x	
Weber, Föster, Stäbler & Paetzold	2017	x		x								x		x	
Slatineau, Dodun, Coteata, Dulgheru, Dusa, Banciu & Besliu	2017	x		x									x	x	
Sadeghi, Houshmand & Valilai	2017	x	x	x							x			x	x
Nagit, Slatineanu, Merticaru, Ripanu, Mihalache, Tabacaru & Boca	2017	x		x							x			x	
Houshmand & amani	2017	x			x						x			x	
Modrak & Soltysova	2018	x		x									x	x	
Iino & Nakao	2018	x		x							x			x	
Oh	2018	x		x							x			x	
Wang & Liu	2018	x		x							x			x	

Rolli, Fradinho, Giorgetti, Citti & Arcidiacono	2018	x								x		x		x	
Nakao & Iino	2018	x		x							x			x	
Wang & Lu	2018	x		x								x		x	
Delaš, Škec & Štorga	2018	x								x			x	x	
Siri & Cochran	2018	x		x							x			x	
Thomas & Pam	2018	x			x							x		x	
Dodun, Panaite, Dusa, Nagit, Coteata & Slatineau	2018	x		x							x			x	
Smith, Shah & Cochran a)	2018	x			x						x			x	
Smith, Shah & Cochran b)	2018	x			x						x			x	
Kujawa, Weber, Puik & Paetzolf	2018	x				x						x		x	
Parretti, Rolli, Pourabbas & Citti	2018	x						x			x			x	
Egger, Riedl, Rauch & Matt	2018	x		x							x			x	
Puik & Ceglarek	2018	x		x								x		x	
Gualtieri, Rauch, Rojas, Vidoni & Matt	2018	x				x					x			x	
Rauch, Vickery, Garcia, Rojas & Matt	2018	x					x				x			x	
Martins, Fradinho, Cavique, Gabriel-Santos, Martinho & Mourão	2018	x				x					x			x	
Cavique, Fradinho, Gabriel-Santos, Mourão & Conçalves-Coelho	2018	x		x							x			x	
Pallaver, Qaddoura & Do	2018	x			x						x			x	
Vossebeld, Foley & Puik	2018	x		x									x	x	
Herjólfsson, Helgason, Ingvason, Pórarinsson & Foley	2018	x		x							x			x	
Lee & Park	2013	x		x									x	x	
Dai, Ge & Zhou	2015	x			x							x		x	
Cheng, Xiao, Gu & Cai	2014	x	x	x									x	x	
Bahadir, Cebi, Kahraman & Kalaoglu	2013		x		x						x				x
Bahadir & Satoglu	2014		x					x			x				x
Li, Chu, Chen, Liu & Shen	2014		x					x			x				x
Ruijun, Jiwei, Qingxuan, Xiaowei & Mingxiao	2014		x					x					x		x
Chen, Chu Sun & Li	2015		x		x						x				x
Chen, Chu, Sun, Li & Su	2015		x					x				x			x
Khandekar & Chakraborty	2016		x					x			x				x
Cui, Ren, Yang & Zeng	2016		x							x	x				x
Cebi, Ilbahar & Atasoy	2016		x					x			x				x
Kahraman, Cebi, Onar & Oztaysi	2017		x							x			x		x
Seiti, Hafezalkotob & Fattahi	2018		x					x					x		x
Kahraman, Cebi, Onar & Oztaysi	2018		x							x			x		x
Du, Cao, Chen & Wang	2013	x		x								x		x	

Maldonado, Garcia, Alvarado & Balderrama	2013		x	x									x		x
Matt	2013	x				x					x			x	
Morrison, Azhar, Lee & Suh	2013	x		x									x	x	
Song & Zhang	2013	x			x						x			x	
Soni, Khanna & Tandon	2013	x		x								x		x	
Arsenyan & Büyüközkan	2014	x					x					x		x	
Atalay & Eraslan	2014		x	x								x			x
Beng & Omar	2014	x	x	x							x			x	x
Farid	2014	x			x							x		x	
Park	2014	x								x	x			x	
Roohnavazfar, Houshmand, Zarandi & Mirsalim	2014	x		x								x		x	
Taha, Soewardi & Dawal	2014	x			x						x			x	
Cao, Qian, Zhang & Lin	2015	x		x									x	x	
Chen, Chu, Yang, Sun, Li & Su	2015		x					x					x		x
Farid & Ribieiro	2015	x			x						x			x	
Gironimo, Lanzotti, Marzullo, Esposito, Carfora & Siuko	2015	x			x								x	x	
Gu, He, Wei & Ming	2015	x				x						x		x	
Kandjani, Tavana, Bernus, Wen & Mohtamari	2015	x					x				x			x	
Kannan, Govindan & Rajendran	2015		x					x			x				x
Khandekar & Chakraborty	2015		x					x			x				x
Khandekar, Antucheviciene & Chakraborty	2015		x					x			x				x
Khayal & Farid	2015	x			x						x			x	
Kucukyildirim	2015	x		x							x			x	
Kulak, Goren, Supciller	2015		x					x			x				x
Lei, Chun, Bin & Shu-hai	2015	x		x							x			x	
Michaelis, Johannesson & ElMaraghy	2015	x				x							x	x	
Modrak, Krus & Bednar	2015	x		x							x			x	
Rauch, Matt & Dallasegra	2015	x				x					x			x	
Schoonenberg & Farid	2015	x			x						x			x	
Sharma & Cudney	2015		x		x								x	x	
Wang, Su, Mu & Mi	2015	x			x						x			x	
Zheng & Xie	2015		x					x			x				x
Afshari, Peng & Gu	2016	x		x								x		x	
Arsenyan & Büyüközkan	2016		x		x							x			x
Babur, Cevkican & Durmusoglu	2016	x			x						x			x	
Chen, Li, Fan, Zhou & Zhang	2016		x					x			x				x

Cochran, Jafri,Chu & Bi	2016	x				x						x		x	
Khandekar & Chakraborty	2016		x					x			x				x
Kir & Yazgan	2016		x					x				x			x
Wang, Mu & Guo	2016	x				x					x			x	
Worren	2016	x				x					x			x	
Yang, Shanda, Gao, Li, Zhu & Dai	2016	x				x					x			x	
Z.Li, Wang, J.Li, Y.F.Liu, C.J.Liu, Cao & Zhang	2016	x								x	x			x	
Ar. Hafezalkotob & As. Hafezalkotob	2017		x					x				x			x
Büyüközkan & Göçer	2017		x					x				x			x
Büyüközkan, Karabulut & Arsenyan	2017		x					x				x			x
Chakraborty, Mondal & Mukherjee	2017		x	x								x			x
Cheng, Feng, Lin, Liu & Tan	2017		x	x								x			x
Cochran, Arinez, Collins & Bi	2017	x				x						x		x	
Farid a)	2017	x			x						x			x	
Farid b)	2017	x			x							x		x	
Farid c)	2017	x				x						x		x	
Goo, Lee, Seo Chang & Chung	2017	x			x							x		x	
Göhler, Frey & Howard	2017	x		x									x	x	
Hager, Wafik & Faouzi	2017	x				x					x			x	
Karatas	2017		x					x					x		x
Lapinskiene & Martinaitis	2017	x		x								x		x	
Mabrok, Efatmaneshnik & Ryan	2017	x	x							x			x	x	
Pettersen, Erikstad & Asbjørnslett	2017	x			x								x	x	
Schoonenberg & Farid a)	2017	x			x							x		x	
Schoonenberg & Farid b)	2017	x			x							x		x	
Villecco & Pellegrino	2017	x	x		x								x	x	
Çakir	2018		x					x				x			x
Chen, Goh & Zou	2018		x					x				x			x
Delaram & Valilai	2018	x			x						x			x	
Fargnoli, Haver & Sakao	2018	x							x			x		x	
Khandekar & Chakraborty	2018		x					x			x				x
Li, Song, Mao & Suh	2018	x								x			x	x	
Maghsoodi, Mosavat, As. Hagezalkotob & Ar. Hafezalkotob	2018		x					x				x			x
Mizani, Sheikh, Gholami & Sana	2018	x							x		x			x	
Palleti, Joseph & Silva	2018	x								x	x			x	
Rauch, Matt & Dallasegra	2018		x			x					x			x	

Rizzuti & Napoli	2018	x		x								x		x