APPLICATIONS OF ENVIRONMENT-BASED DESIGN (EBD) METHODOLOGY

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ABSTRACT

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Seyed Reza Razavi

A product's environments play a significant role in its development. In other words, any alteration in the environment surrounding a product leads to changes in its features. Hence, having a systematic procedure to analyze the product's environments is a crucial need for industries. Environment-Based Design (EBD) methodology describes the environment of the product (excluding the product itself) and presents a rational approach to analyze it. In order to achieve an efficient product design and development process, EBD utilizes different tools. Recursive Object Model (ROM) diagram, Cause and Effect Analysis, Life Cycle Analysis, Asking Right Question and Answering are EBD's major tools and technics. In this research, we aim to represent EBD's capabilities for product evolution analysis, complex products development and human-centered products development. In order to demonstrate EBD's competences for product evolution analysis, we conduct a case study of braking systems evolution analysis through analyzing the environments around them. Afterward, we perform environment analysis for aerospace design methodology in order to propose a novel design methodology for the aerospace industries. Finally, we propose a course scheduling model based on environment analysis of the academic schedules and we verify our model using Concordia University's courses.

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1. Introduction

Environment Based Design (EBD) methodology is an environment centered methodology which considers everything surrounding a product as its environment. This feature of EBD makes it capable of performing different analyses through extracting different characteristics of a product from its environment. A product can be a mechanical artifact, a service or even a project. Thanks to EBD's ability of providing different tools for environment analysis, this method has been used in wide range of projects, from project management to product development. In this research we aim to utilize EBD for analyzing product evolution, designing complex systems and designing human-centered systems. We utilize EBD in different steps of each project. First, we use EBD for launching and planning of each project. Afterward, we perform detail analysis through using EBD. We show the capability of EBD for product evolution analysis and we perform a case study of braking system evolution analysis by using EBD methodology. In the complex system designing project, we demonstrate EBD approach in coordination with other techniques for designing aerospace products. Considering academic institute as a human centered system and their schedules as a feature of them, we use EBD for analysing environments around course schedules. Following that, we propose a novel scheduling model. We consider product evolution analysis, design methodology for designing a complex system and the course schedule as products of aforementioned projects. Hence, EBD is utilized to manage all three researches in their top levels, whereas it also used in the case-studies of aforementioned projects.

The remainder of this research is organized as follows. Section 1 presents EBD's definition for products' environments and discusses product development tools including design methodologies and management model. Section 2, present a case study of braking system evolution analysis using EBD. Section 3 introduces a novel design model which contains EBD methodology for designing complex product. Section 4 present application of EBD for course scheduling and section 5 concludes the thesis.

1.1. Product's Environments

Product is defined as an item or a service, which is produced for sale (Loch and Stylianos 2008). Product is not an isolated artifact from its environment and its environment is defined as everything except the product itself (Zeng 2004b). We define product and its environment as a system of Product-Environment (Zeng 2004b), where three main ingredients influence the concept of environment: natural; built; and human. Natural environment means natural laws; the built environment includes all artifacts built or created by human beings; and finally, human environment are a group of human that has interaction with the product (Zeng 2004b). Figure 1 demonstrate Product-Environment System (PES) including different parts and environments and different levels of design.

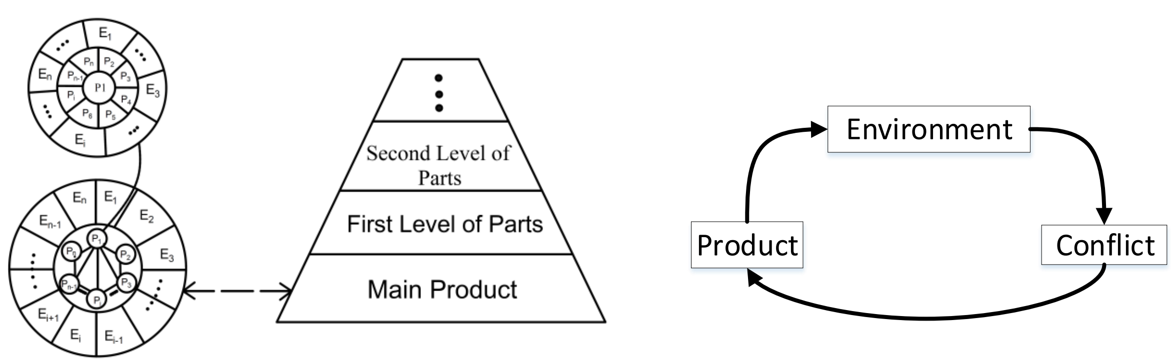


Figure 1: Product Environment system.

In order to analyze different aspects of a product based on its environment, we need to have a clear idea about both product and product environment. Zeng, proposed a formulation to model

Product-Environment System (PES). He defines PES as an object which is presented by "Ω" and it contains Product (S), Environment (E) and the interaction between Environment and Product (E ⊗ S). Figure 2 demonstrates different types of interaction in a given PES.

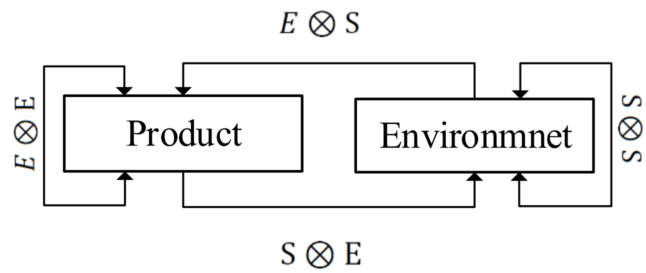


Figure 2: Interaction between product and environment in a PES.

He represents the boundary between environment and product by "B", which contains structural boundary (B^s), actions (B^a) of the environment on the product and responses (B^r) of the product to its environment. Equation (1) presents the mathematical model of PES and Equation (2) presents mathematical model of product and environment boundary.

$$\Omega = E \cup S, \forall S\ [E \cap S = \phi] \tag{1}$$

$$B = B^s \cup B^a \cup B^r, \forall B^s, B^a, B^r\ [(B^s \cap B^a = \phi) \wedge (B^s \cap B^r = \phi) \wedge (B^r \cap B^a = \phi)] \tag{2}$$

The interaction between a product and its environments is interpreted as requirements which must be satisfied by product. Hence, detailed description of different environments around product can help to identify the aforementioned requirements.

As it was previously mentioned, environments around a product are classified into Natural, Built and Human environments. A product must follow all the natural laws, otherwise it will not exist. Friction law, Newton Law, snow and rain are the different examples for natural environments around a product while safety and reliability are the examples of natural requirements with respect to natural environments. We consider all of artifacts which are built by human beings as the built environment. For instance, software or a building involved in this category and product must satisfy requirements such as manufacturability and transportability as a result of having interaction with built environments. Finally, human environments include human who have interaction with the product. Designer, manufacturer, seller, transporter and customer are the examples of human environments. Salability, operability and maintainability are considered as the requirements, which are related to human environments. We present natural, built and human environments by E^{n}, E^{b} and E^{h}, respectfully and equation (3) describes the mathematical model for a product's environments (Zeng 2004b).

$$E = E^b \cup E^h \cup E^n \tag{3}$$

We consider the product and the environments around it as the different components in a PES until the moment at which the product is developed and released to the market. In other words, a product becomes new part of environment for the future products as soon as it is released to the market. This fact is very crucial for evolving the product and its environments through times. In this section we described the product and environments around it, interaction between them and different types of environments. In the next section product development is describe in detail.

1.2. Product Development

Strategy of manufacturers for product development plays a significant role in their competition in the market. Plans, tools and techniques which they utilize for the product development are the most effective factors for their success. Product development is the set of activities starting with the perception of a market opportunity and ending in the production, sale, and delivery of a product (Loch and Stylianos 2008). Product development consists of product marketing, product designing and product manufacturing whereas project management is along with all of them.

Product management plays a significant role in fixing all three elements beside each other to bring a new product or service in the market (Loch and Stylianos 2008).

Although marketing and manufacturing are important elements of product development, in this research we focus on analyzing impacts of design methodologies and management theories on final product. Project management includes market research and marketing analysis, human management, time management, budget management, reliability management and many other aspects. Designing of a product is defined by conceptual, preliminary and detailed designs and it is directly related to different levels of manufacturing and assembly. Therefore, combination of design methodologies and management theories play a significant role in having a successful product. In this section, well-known design methodologies and product management tools and techniques, which will be utilized for our research, are presented.

1.2.1. Design methodologies

The objective of a design methodology is to provide rational approach for completing a design task, which is to turn customer needs into product solution. Debates and discussions have been made to distinguish among definitions and scopes of design methodologies and we will review a few design methodologies in this section.

As a result of the design method movement in the 1960's, the systematic design methodology was proposed to consider formulation, synthesis and evaluation as the basic components of a design process (Pahl et al. 2007; Pugh 1990; Adams 2015; Hubka and Eder 1988; Hubka and Eder 1987; Eder 2010). The formulation aims to specify design requirements, the synthesis produces design solutions by making use of existing design knowledge, whereas the evaluation assesses the performances of design solutions against the formulated design requirements. Pahl describes systematic engineering design in four stages, which are product planning, conceptual design, embodiment design and detailed design, where problem formulation, synthesis and evaluation are utilized in all of those four stages(Pahl et al. 2007). Pugh proposed total design methodology to transform market needs to products, which consists of six stages: development of the market and feasibility studies, product design specifications (PDS), conceptual design, detailed design, manufacturing and product sales (Adams 2015; Pugh 1990; Pugh 1989). Hubka and Eder also presented the theory of Technical Systems (TS), which is considered at different levels including black box, function structure, organ structure and component structure (Hubka and Eder 1987; Hubka and Eder 1988; Eder 2010). All of systematic design methodologies aim to transform design requirements into detailed product specifications.

The first component of systematic design is problem formulation and Quality Function Deployment (QFD) is well defined to support this stage of design. QFD was introduced by Akao (Chan and Wu 2002; Akao 1972) to analyse the quality of a design to relate customer requirements and technical characteristics through House Of Quality (HOQ). QFD has been widely utilized to capture customer's requirements. The HOQ contains six rooms: customer requirements, technical characteristics, relationships between customer requirements and technical characteristics, correlation between technical characteristics, planning and target.

Another important component of systematic design methodology is to find potential solution for a set of design requirements through synthesis. General Morphological Analysis (Problem-Solving) proposed by (Zwicky 1969; Zwicky and Wilson 1967) is a method to serve such a purpose. While General Morphological Analysis can well support designers in routine design, (Altshuller 1984; Orloff 2006)also proposed theory of inventive problem solving (TRIZ) to resolve design contradiction through abstracting of a design problem. TRIZ suggests the solution based on a list of proposed principles which are derived from huge amounts of patents and common tricks utilized to solve similar problems. A backbone for systematic design methodology is the concept of function and functional structure. In the past three decades, a few function-based model of design has been developed, including Function-Behavior-Structure (FBS) (Gero 1990; Hybs and Gero 1992; Gero and Kannengiesser 2004), Function-Behaviour-States (FBS) (Umeda et al. 2010; Y. Umeda et al. 1990) and Structure-Behavior-Function (SBF) (Goel, Rugaber, and Vattam 2009). The function-based design methodologies mostly serve synthesis part of design process, while they slightly consider formulation and evaluation also.

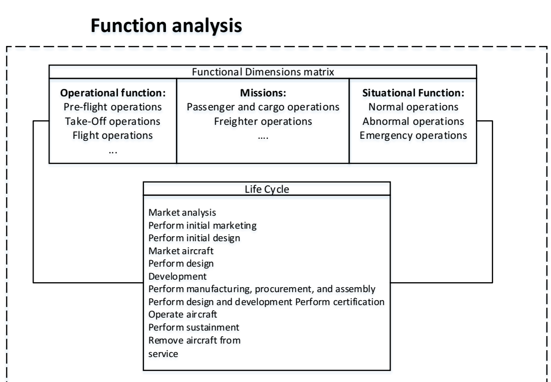
In order to evaluate design solution and perform the third dimension of design process, Axiomatic design theory (Suh, Bell, and Gossard 1978a) proposed by Suh. Axiomatic Design (AD) theory was proposed to analyse the quality of design solution. Based on Axiomatic Design the optimal design solution includes independent Functional Requirements (FRs) and minimum level of information (Suh, Bell, and Gossard 1978a;Suh 1990; Borgianni and Matt 2016; Ogot 2011). Zig-Zag process is the nature of design problems, which has been considered in the literature (Simon 1973; Suh 1990; Zeng and Cheng 1991; Maher, Poon, and Boulanger 1996; Dorst and Cross 2001; Hatchuel and Weil 2003). Simon (1973) introduced moving from the initial states to the goal state as a feature of well-structured problem. Suh (1990) also consider a zigzagging process between customer, functional, physical and process domains to decompose functional requirements, design parameters and process variables. Zeng proposed recursive logic for design problems (Zeng and Cheng 1991) which was later confirmed by Roozenburg (1992). He represented that design is largely different from deduction, induction and abduction, where design problem and solution are evolved through a recursive process between design and problem spaces simultaneously. Maher and Tang (Maher and Tang 2003; Maher, Poon, and

Boulanger 1996) and Dorst and Cross (2001) presented design problem as the co-evolution of problem and solution spaces. Following the aforementioned attempts in design science, C-K theory (Hatchuel and Weil 2003) viewed the design problem as the interaction of knowledge and concept spaces and tries to model design problem by Expansion, Disjunction and Conjunction activities between spaces.

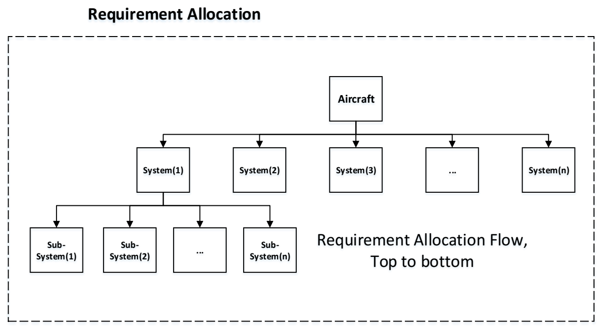
According to the all aforementioned design methodologies, design problem is a recursive and open-ended process, which can lead to an uncertain situation. In order to overcome this problem, Zeng proposed Environment-Based Design (EBD) methodology based on recursive logic of design (Zeng and Cheng 1991) to supervise the zig-zag process of design from the initial problem state to the final solution state. Environment-Based Design methodology views design as a process in that the existing environment is changed to have a more desirable environment. In other words, everything in design process starts from environment, changes environment and comes back to environment. In this methodology everything around design solution is an environment for it and design solution is became part of environment after generating and making changes in the environment which leads to evolution of design solution. Recursive Object Model (ROM) diagram, Cause and Effect Analysis and Life Cycle Analysis, Asking Right Question and Answering tools helps designer to analyze design problem in EBD methodology. EBD takes description of a situation, even tendency of inventing and/or designing new product as the inputs of analysis and product development specification including the final product, the product environment, design requirements and constraints, design knowledge, synthesis report and evaluation report is the output of its design process. In other words, EBD can start a design problem from scratch and will finish it with a complete product description (Zeng 2004b, 2007).

1.2.2. Systematic Design - System Engineering approach

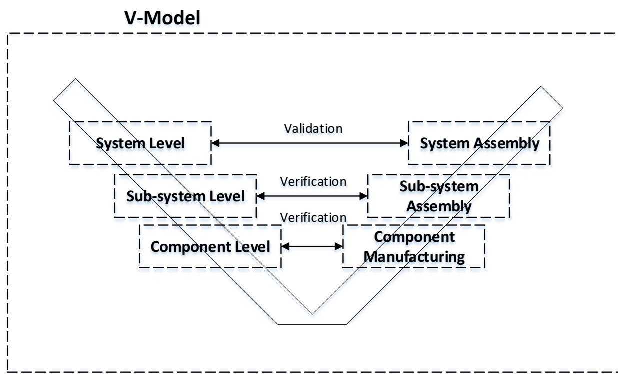
Systems engineering is an interdisciplinary field of engineering for solving complex problem. During system engineering process different tools including work break down structure, configuration management, technical review and audit, risk management and many other technics are used. Function analysis, requirement and constraints analysis, top level and subsystem synthesis, validation and verification are different steps of SE process. Function analysis is the first stage of SE and it is the predecessor for requirement analysis (identification and allocation). Function analysis is essential for new product and it can be done partially for new version of product or any update in the product. AC life cycle analysis, Functional Flow Block Diagram (FFBD) and Functional Dimensions Matrix, Integrated Definition for Function Modeling (IDFM), the Cluster model and Swim Lane model are useful technics, which can help designer to recognize the functions and their interaction (Jackson 2014). Figure 3 represent different activities in System Engineering.



(a)



(b)



(c)

Figure 3. System Engineering Steps, (a) Function Analysis (b) Requirement Allocation (c) V-Model (Jackson 2014)

In System Engineering (SE) approach, functional requirements, regulatory requirements and constraints must be recognized after function analysis and requirements must be allocated to systems, subsystems or components in each level of design. Subsystems interaction analysis and requirement-solution space evolution are the SE tools for requirement analysis. Synthesis starts from initial concept or Top-level synthesis, trade-off and System Design Review (SDR) and will continue by subsystem synthesis, subsystem trade-off and Preliminary Resign Review (PDR). For complex product designing, top level synthesis includes sizing, system requirements and constraints consideration and system architecture identification and subsystem synthesis deals with primary performance requirements and constraints of subsystems. Considering SE process, we must perform requirement validation at first steps of any project, verification through whole stages of design and product validation at last stage of project (Jackson 2014; Jackson 1997). Interface analysis, System Safety analysis, Large-Scale System Integration (LSSI) and product Resilience analysis are other SE techniques (Jackson 2014; Jackson 1997). Figure 3. Represents function analysis (a), requirement allocation (b) and verification and validation (c) processes of System Engineering (SE).

1.2.3. Environment-Based Design Methodology

The EBD is an environment-centred design methodology, which includes three activities: environment analyses, conflict identification, and solution generation as shown in Figure 4. It decomposes the recursive dependence among design problems, design solution, and design knowledge, as was formulated in the logic of design (Zeng and Cheng 1991). It was derived mathematically that design problem, design solution, and design knowledge are all implied in an environment system (Zeng 2004b; Nguyen and Zeng 2012). Consequently, a design process can be proceed by decomposing product's environments (Zeng and Gu 2001).

Recursive Object Model (ROM) diagram, Cause and Effect Analysis and Life Cycle Analysis, Asking Right Question and Answering tools helps designer to analyse design problem in EBD methodology. EBD presents description of a situation, even tendency of inventing and/or designing new product as the input for its process. Product development specification including the final product, the product environment, design requirements and constraints, design knowledge, synthesis report and evaluation report is output of EBD's design process. In other words, EBD can start a design problem from scratch and will finish it with a complete product description (Zeng 2007; Nguyen and Zeng 2012; Zeng 2004a). Figure 4 represents different activities and relation of product and environment in EBD methodology.

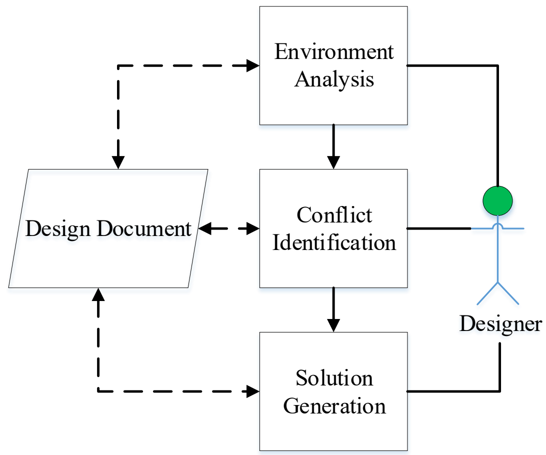


Figure 4: EBD activities and their interactions.

ROM diagram is the main tool of EBD for analyzing design and evolution process. It consists of two types of objects and three kinds of relations which are described in Table 1.

Table 1. ROM diagram's elements and their definitions (Zeng 2014)

Type		Graphic	Definition
Objects	Object	o	Everything in the universe is an object
	Compound object	o	It is an Object that includes at least two other objects in it.
Relations	Constraint		It is a description, Limitation or particularizing relation of one object to another
	Connection	ι	It is to connect two objects that do not constrain each other
	Predicate	ρ	It describes an act of an object on another or that describes the states of an object.

Three stage of EBD including environment analysis, conflict identification and solution generation are presented as follows.

1.2.3.1. Environment Analysis

Given an initial design problem statement as the input, the environment analysis identifies the product to be designed, the explicit and implicit components of product environment, and the mutual interactions between the product and the environment components and between the environment components following the three activities below:

a) Determine solution directions by asking design questions based on a design problem statement
b) Clarify the design problem statement by answering questions following the solution direction
c) Formulate Product-Environment System from a design problem statement (Zeng 2014)

1.2.3.2. ROM analysis

The first step in determining the solution direction is to understand the design problem statement. This understanding can be achieved through one's personal capability and experience; however, in EBD, the understanding process is assisted by the ROM analysis process which transforms the original design problem statement described by natural language into a ROM diagram.

The second step in determining the solution direction is to identify the objects that need to be questioned and the sequence to question them by using the design problem statement ROM diagram as the input. This is completed in four steps as following (Zeng 2014):

1) Code objects in the ROM diagram: Every object in the ROM diagram is assigned a number in a continuous manner.
2) Construct ROM matrix: A coded ROM diagram can be represented in a matrix form by assigning relations according to following rules.

$$r_{ij} = \begin{cases} 1 & \text{objects } i \text{ and } j \text{ have a subject - verb relation} \\ -1 & \text{objects } j \text{ and } i \text{ have subject - verb relation} \\ 2 & \text{objects } i \text{ and } j \text{ have a verb - object relation} \\ -2 & \text{objects } j \text{ and } i \text{ have a verb - object relation} \\ 3 & \text{there is a constraint relation from object } i \text{ to object } j \\ 0 & \text{otherwise} \end{cases}$$

i. **Rank ROM objects:**

We rank object according to the number of constraint and predicate relations on the objects in the ROM diagram (Zeng 2014).

ii. **Define object list for questioning:**

An object list will determine when to ask questions about which object. Using the information in in Table 2 can be applied to find the order of questioning objects for design-related tasks. Rules can be different for different applications (Zeng 2014).

Table 2. Rules for finding objects to question (Zeng 2014)..

Rule 1	Among all of the candidate objects, the object with the most undefined constraints and predicates should be asked first.
Rule 2	Before an object can be asked a question, the objects constraining or predicating them should be asked.

1.2.3.3. Generate questions

The third step in determining the solution direction is to generate questions for the object identified in the previous step. A sample question template is given in

Table **3** to generate questions for an identified object. It must be noted that this template is by no means complete and the readers can develop their own refined ones based on a comprehensive experiment and/or on different purposes (Zeng 2014).

Table 3. Rules for finding objects to question (Zeng 2014).

#	Conditions	Question template
T1	For a concrete, proper, or abstract noun object N without any constraint	What/Who is N?
T2	For a concrete, proper, or abstract noun N with an adjective constraint A	What is A N?
T3	For an noun object A constraining an noun object N	What is A? What is/are A N?
T4	For a verb V with its subject N1 and object N2	What do you mean by V in

		the statement "N1 V N2"? How do/does N1 V N2? Why do/does N1 V N2? When do/does N1 V N2? Where do/does N1 V N2?
T5	For a verb object V constrained by an adverb A with its subject N1 and object N2	What do you mean by V A? Why do/does N1 V A N2? When do/does N1 V A N2? Where do/does N1 V A N2?
T6	For a verb V with an object N, but missing its subject	What/Who V N?

1.2.3.4. Answering design related questions

Answers to design-related questions must serve the purpose of environment analysis by providing the information sufficiently and necessarily available at the moment that can assist in the identification and definition of the explicit and implicit components of product environment, and the mutual interactions between the product and the environment components and between the environment components. A guideline is provided in Table 4 to guide the answering of the listed questions.

Table 4. Guideline to answer questions (Zeng 2014)..

#	Questions	Guideline
G1	What/Who is N? N: a concrete, proper, or abstract noun object What is A N? A: an adjective constraint	a) If (A)N is the product to be designed, then the answer should address 1) the purpose of (A)N; 2) the definition of (A)N; b) Else, if N is an environment component of a product, then the answer should define (A)N; c) Else, the components and attributes of N should be described.
G2	What/Who do/does V N? V: a verb	For N1 that V N, the answer should define the components and attributes of N1 in the context of V.
G3	When do/does N1 V N2? When do/does N1 V A N2?	The answer may assume one of the following two forms: a) In/On a time, N1 V(A) N2; b) When/During/While N3 Va N4, N1 V(A) N2.
G4	Where do/does N1 V N2? Where do/does N1 V A	The answer may assume one of the following two forms: a) In/Along/Through a place, N1 V(A) N2;

	N2?	b) N3 Va N4, where N1 V(A) N2.
G5	Why do/does N1 V N2? Why do/does N1 V A N2?	The answer should be organized as: To Va Na, N1 V (A) N2.
G6	What do you mean by V? What do you mean by V A? How do/does N1 V N2?	a) If the subject (N1) or object (N2) of V is not the product, then the answer should include all activities included in V-ing in the context of N1 and N2; b) Else, skip the question and leave for solution generation.

1.2.3.5. Formulation of Interaction Dependency Network

The purpose of design is to construct a well-defined performance network, which is also a product-environment system, from an ill-defined one. However, during the design process, the product-environment system implies an ill-defined performance network, in which necessary conditions are missing to achieve a design function. Hence, at each intermediate stage of conceptual design, one can only identify existing necessary conditions for each given interaction. Naturally, the output of the environment analysis will be an interaction-dependency network, which implies the dependency relations between two interactions. In previous sections, we identified product and its environment components as well as some relationships between them. This section will identify interactions in a product-environment system and the dependency relations between interactions. “interaction” is defined as a relation from one object to another object that will generate a new object. Interaction includes action that is on an object from its environment and reaction that is from an object to its environment. A dependency relation from an interaction I_m to another I_n refers to a situation where the presence of I_m will lead to the occurrence of I_n. The output of the environment analysis process will be an interaction dependency network composed by interactions and their dependency relationships as it is presented in following Figure (Zeng 2014)..

	I_1	I_2	I_3	I_4	…	I_{n-1}	I_n
I_1	0	0	0	0	0	0	0
I_2	0	0	3	0	0	0	0
I_3	0	0	0	0	0	0	0
I_4	0	0	0	0	3	0	3
…	0	0	3	0	0	0	3
I_{n-1}	0	0	3	0	0	0	0
I_n	0	0	3	0	0	0	0

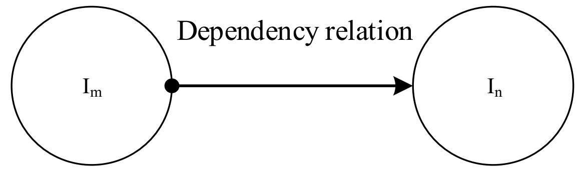


Figure 5: Interaction matrix and cause and effect diagram (Zeng 2014).

1.2.3.6. Conflict identification

Conflicts are the driving force of product evolution in EBD analysis. Conflict identification starts with analyzing Interaction Dependency Network and followed by Environment Components' Interactions analysis. In the Interaction Dependency Network, the interactions that have same resources can be sources for the reactive conflict. Also, the active conflict can happen if there is an effect without any cause.

1.2.3.7. Solution generation

After identifying active and reactive conflict, we must utilize Asking Right Question and Answering tool and ROM diagram to resolve the identified conflict. We again analyze the ROM diagram and we find core of ROM. Afterward, we start asking question about core's constraint and predictors. Following this procedure help designers to have more clear idea about solution.

1.1. Product Management tools and techniques

In current century, product development management has different aspects. Drastic changes and complexity of product force companies to make their decisions very concurrent. In this section, project management and its related techniques for supporting rapid changes of market, complex product development and decision making are presented.

1.1.1. Project Management

A project has different steps of initiating, planning, executing, controlling and monitoring, supporting and closing. The project initiation can be expanded to feasibility study, project selection, project preinitiation and project initiation (Project Management Institue 2017). Project management has different aspect of integration and scope, cost, time, quality, risk, human resource and procurement management. On the other hand a product has a life cycle which is strongly related to project's steps. We define idea generation, idea evaluation, specification consideration, early configuration and market analysis, strategic analysis, design, fabrication, assembly components or systems testing, verification, market test and evaluation, product support service and maintenance and disposal as the life cycle of a product (Markish 2002; W. Spitz et al. 2001). Relationships between project stages and product life cycle and their tools and techniques are presented in Table 5.

Table 5. Product life cycle and project steps interrelations

Project steps	Product Life cycle stages
Feasibility Study	Idea generation, Idea evaluation, Specification Consideration, Early Configuration and Market Analysis
Technical, Marketing, Resource, operational, schedule and financial feasibility studies	
Project Selection	Strategic Analysis
SWOT analysis, Weighting scoring method, NPV, ROI and Payback analysis	
Project-Preinitiation	Strategic Analysis
Business plan developing	
Project Initiation	Strategic Analysis
Stakeholder management, project charter development, kick off meeting holding	
Project Planning and Execution	Design, Fabrication, Assembly Components or Systems Testing
Human resource management, scope management, Quality management, Cost management, Procurement management, Risk management, Project progress report	
Monitoring and Controlling Phase	Product Test, Market Test and Evaluation
Quality Assurance (QA), Quality Control (QC), Risk monitoring and controlling, Procurement monitoring and controlling, Cost monitoring and controlling, Time monitoring and controlling	
Support Service	Maintenance
Closing	Disposal
Reuse, Remanufacture, Recycle, Combustion, Landfill	

1.1.2. Agile project management

Aerospace industries face challenges of rapidly changing of world, and consequently more demanding requirements and more difficult competition. All these can lead to increasing of team size and expanding of development cycles, increasing of costs or even developing an unaffordable product (Belie 1993). Agile project management has been used in software development and it can also be implemented in mechanical product project. Managing the changing priorities is most important characteristic of agile approach. Scrum is one of agile project management methods. In contrast to the sequential Waterfall framework, Scrum framework is an iterative and incremental framework. The Scrum framework allows easier and less costly reaction to new information and unexpected change and it includes several events, roles and artefacts. Boeing uses Agile Scrum SE beside Agile Software (SW) development. The Product Backlog, the Sprint Backlog, Sprint Planning meeting, daily Scrum Meeting, sprint Review and sprint Retrospective are tools and events in scrum methodology (Reynisdottir 2013). Scrum idea can guarantee the online fixation of problems during project. In other word Scrum method helps producers to divide the main project to small sprints which can help aerospace industries to solve design problems before main design review (Reynisdottir 2013). Scrum methodology's framework and events are presented in Figure 6 .

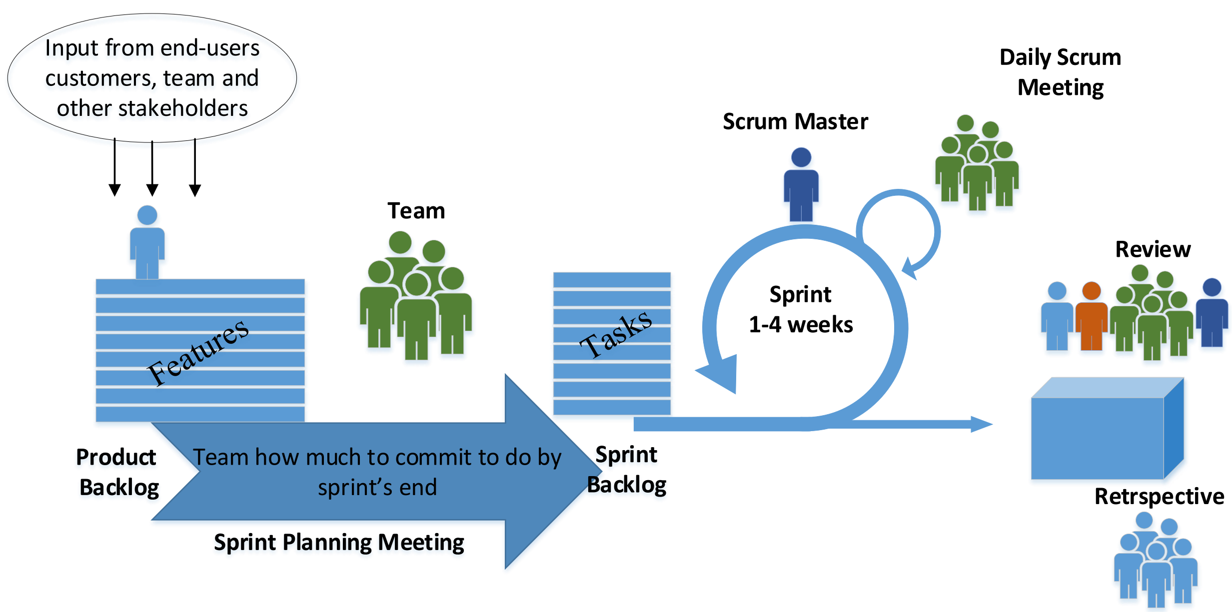


Figure 6: Scrum framework and events (Reynisdottir, 2013).

Lean manufacturing is also another agile methodology which is utilized to maximize customer value while minimize waste. In this methodology focus will be changed from vertical department and technologies optimization to the flow of products. Specifying Values, map and value stream identification, organizing product fast flow, pulling and perfection are different steps of lean manufacturing. Waste elimination based on seven forms of wastes is part of map and value stream identification and 5S is another technique which is used in fast flow step (Jones and Womack 2010). Choosing best production layout among process layout, product layout or Cell production layout, setup time reduction and pull based production are also other lean production tools and techniques(Jones and Womack 2010). Lean manufacturing idea and Kanban can help aerospace industries manager to find bottlenecks (Kniberg 2009; Tutorialspoint 2016).

Combination of Lean method with trade off study, which is called Lean Product and Process Development (LPPD) is also helpful during System Development and Integration (SD&I) (Al-Ashaab et al. 2013). Al-Ashaab utilized LeanPPD model in designing of a helicopter engine for Rolls Royse. LPPD includes Set-Based Concurrent Engineering (SBCE) idea and it guarantees a set of solutions at the system level rather than a single solution. LPPD has 5 steps of value research, map design space, concept set development, concept convergence and detailed design (Al-Ashaab et al. 2013)

1.1.3. Decision Support Systems

Decision making is indivisible part of all stages of product development. AHP, AD and Decision Trees are well-known technics in decision support systems. AHP, introduced by Thomas Saaty, is an effective multi-criteria decision-making method. Briefly, it tries to find ratio scales from pairwise comparisons. AHP helps designers to realize order of design requirements (Saaty 2000). Considering product as a solution for a design problem, AD can be employed to make decision in verification and validation of product. According to axioms and corollaries of AD model an uncoupled design solution with minimum level of information is acceptable (Suh 1990; Suh, Bell, and Gossard 1978b). Decision Trees also can help AD model in decision making. FDT is one type of Decision Trees which can be utilized in complex designing procedures and it aims at combining the ability of decision trees (to learn from examples, to present knowledge in comprehensible form) with fuzzy representation (to deal with inexact and uncertain information). FDT is based on previous data sets, not expert judgment and Fuzzy partitioning (clustering), training and testing based on Fuzzy ID3 learning methodology are different steps of FDT (Evans et al. 2011). Considering complexity of decision making in complex project such as AC designing, we need to utilize combination of tools and techniques. Agile Decision Support System (ADSS) is designed to support complex decision making and it is a combination Modelling and Simulation (M&S), artificial intelligence, data mining and experts' suggestions (Li et al. 2016). In this research, we also aim at combining decision support systems with management and design methodologies for improving current aerospace design methodologies.

2. EBD Approach for Product Evolution Analysis-Case Study of Braking System

Effective and efficient analysis of product evolutions is a significant value-driver for a manufacturer to make strategic decisions. In order to analyse product evolution for helping industries to capture future of a product, we need to utilize a good methodology. Hence, a deep understanding of product evolution analysis is needed. We perform ROM diagram analysis to realize most effective object of the statement. ROM diagram for the problem statement is illustrated in Figure 7.

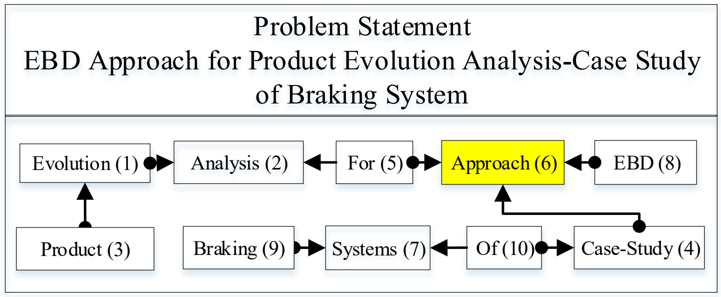


Figure 7: ROM diagram for Problem Statement: EBD approach for product evolution analysis-Case Study of braking system.

Afterward, we utilize ROM matrix and ranking analysis to understand core of diagram and order of objects for questioning. ROM matrix and rankings are presented in Table 6.

Table 6: ROM matrix and rankings: EBD approach for product evolution analysis-Case Study of braking system

(a)

Object	1	2	3	4	5	6	7	8	9	10
1	0	**3**	0	0	0	0	0	0	0	0
2	0	0	0	0	**-2**	0	0	0	0	0
3	**3**	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	**3**	0	0	0	0
5	0	**2**	0	0	0	**3**	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	**-2**
8	0	0	0	0	0	**3**	0	0	0	0
9	0	0	0	0	0	0	**3**	0	0	0
10	0	0	0	3	0	0	**2**	0	0	0

(b)

Number of relations	3	2	1
Object	6	7	1, 4, 5, 10
Questioning object list	(2, 1, 3), (9, 7), (8, 4)		

We can understand from ranking of objects that "product", "evolution" and analysis are the first objects to be questioned. Hence, we consider "product evolution analysis" for the further analysis. Afterward, we ask question about "EBD-design methodology" and "braking system Case-Study".

We consider product evolution analysis as a product and we analyse environment around it to identify the best methodology, which helps to perform product evolution analysis. As discussed earlier, the environment around a product consists Built, Human and Natural environments. Therefore, we classify environment around product evolution analysis and extract the details of each environment by using Asking Right Question and Answering tool. There is not any component in Natural environment for product evolution analysis. We consider that product evolution can be viewed as a process in which a product is collectively designed by its customers, investors, engineers and society at large. As a result, a design methodology can be used to understand how a product has been and may be evolving under various business, technological and social situations. Consequently, design methodologies are considered as a part of Built environment and designers are classified in Human environment. Table 7 presents environment around product evolution analysis.

Table 7: Different environments around product evolution analysis

Different Types of Environments	**Environment's Components for Product Evolution Analysis**
Natural	NA
Built	Design methodologies for product evolution analysis
Human	Designers and Managers

In order to understand each component of environments for product evolution analysis, we utilize Asking Right Questions and Answering tool to expand our information about each component. Outputs of Asking Right Question and Answering analysis, which includes the most important information about environments' components, are presented in the Table 8.

Table 8: Asking Right Question and answering for product evolution analysis's environments' components

Questions	**Answers**
Which design methodologies is	Design methodologies which can analyze product evolution must be

capable of product evolution analysis?	capable for defining the driving forces of product evolution, identifying necessary resources of product evolution and deriving potential directions of product evolution.
How can capability of a design methodology for product evolution analysis be recognized?	A case study must be performed to verify effectiveness and efficiency of any design methodology for product evolution analysis.

Therefore, a good design methodology that can be used to analyze product evolutions must be capable of the following:

1) Defining the driving forces for a product evolution to start;
2) Identifying necessary resources for a product evolution to happen; and
3) Deriving potential directions for a product evolution to move along.

EBD as an environment centered design methodology can be utilized for product evolution analysis. In order to study EBD methodologies in terms of its capabilities for product evolution analysis, we need to assess it based on following two criteria. First if it consider driving forces of product evolution, resources for product evolution and direction of product evolution in its methodologies and second if it has tools and techniques to perform the aforementioned aspects of product evolution analysis.

EBD considers conflicts as the driving force of design and it introduces Cause and Effect analysis and Environment Component Interaction analysis as tools and techniques to extract these driving forces. Moreover, EBD utilizes the environments around product as resources for designing product and consequently for product evolution analysis and it has tools and techniques including Environment Analysis, Life Cycle analysis, ROM diagram and Asking Right Question and Answering for identifying resources. Considering that EBD methodology has three main ingredients of conflict identification, environment analysis and solution generation, deriving the solution in design process is indivisible part of EBD. ROM diagram and Asking Right Question and Answering help designers for obtaining the solution during EBD processes.

In order to find out capabilities of EBD methodologies for product evolution analysi, we need to conduct a case study to analyze effectiveness and efficiency of it. Hence, we analyze braking system evolution by using EBD in the next section and consequently the trend of braking systems evolution will be extracted to find the future of them.

2.1. Evolution analysis of braking system using Environment-Based Design

A braking system is a device to slow down or stop a moving vehicle and hold a stationary vehicle or object at rest. In this survey, braking systems are taken as an example to illustrate how EBD can be used to analyse the evolution of a product.

The environment can be considered as an existing situation, which consists of the present product, its customers, engineers, investors, science and technologies, and society as well as their interactions. EBD produces a new product from the present environment. Using EBD, product evolution can be analysed through environment analysis, conflict identification and solution generation.

2.1.1. History of braking system

The objective of a Braking system is to slow down and/or stop a moving vehicle and to keep a stationary vehicle from moving. Significant evolutions have occurred to braking systems due to the advent of new technologies. We can analyse evolution of braking systems by looking into how major environment components changed around them. In this subsection, we will briefly present the history of braking system.

As the earliest braking system, the External Shoe brake was invented by Nicolas Joseph Cugnot in 1769, followed by Compressed Air External Shoe brake in 1875 (Carley and Mavrigian 1998). After pneumatic tires were invented in 1841, External Shoe brakes were replaced by Contracting Band brakes and with the appearance of steel alloys Internal Expanding brakes came. By the advents of hydraulic system, servo motors and new frictional materials, Hydraulic brake system, Power Assisted brake systems and Disc brake systems were invented one after another (Hasegawa and Uchida 1999; Carley and Mavrigian 1998; Duffy 2009). Finally advances in electronic and controlling engineering led to have the invention of Anti-Lock brake system and Vehicle Dynamic Control systems (Carley and Mavrigian 1998). The evolution flow of braking systems along with technology changes is illustrated in Figure 8 .

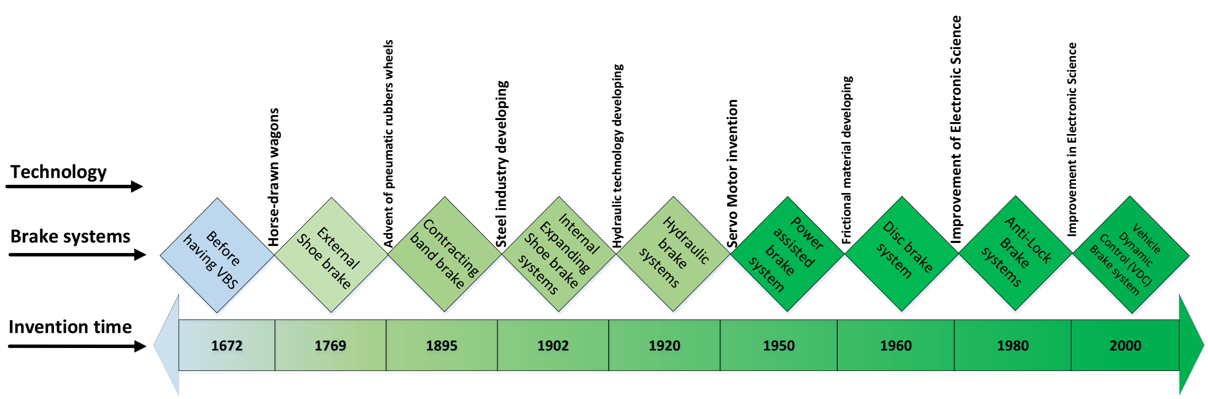


Figure 8: Evolution of braking system along with technology changes.

In the following section, we will analyse how the evolutions above happened using the EBD methodology. Then, a trend analysis for braking systems will be presented, based on which, a prediction for future of braking system is performed.

2.1.2. EBD analysis of braking system evolution

Nonexclusively, the problem of designing a brake system can be stated as the following:

Driver intention to stop and slow down a vehicle should be satisfied effectively and efficiently.

The analysis of brake system evolutions is to identify the driving forces behind the evolutions and how the evolutions have happened. Each cycle of evolution is indeed a design, which would trigger a new cycle of evolution. In this subsection, the EBD will be used to show how each generation of brake system was collectively designed.

2.1.2.1. Environment Analysis

The first activity in the EBD is environment analysis, which aims to define the current product-environment system. The output of environment analysis is identified environment components and the relationships between these components, together with an abstract reference to the product

Environment analysis consists of the following steps:

- Determine solution directions by asking design questions based on a design problem statement
- Clarify the design problem statement by answering questions following the solution direction
- Formulate Product-Environment System from a design problem statement Step

1. Asking Design Questions

The questioning strategy supports an efficient and effective determination of a good solution direction based on a design problem statement. It includes three activities of ROM analysis, defining objective list and generating questions.

Drawing the ROM diagram from the problem statement is the first step. Figure 9 is the initiative ROM diagram for the design of a braking system.

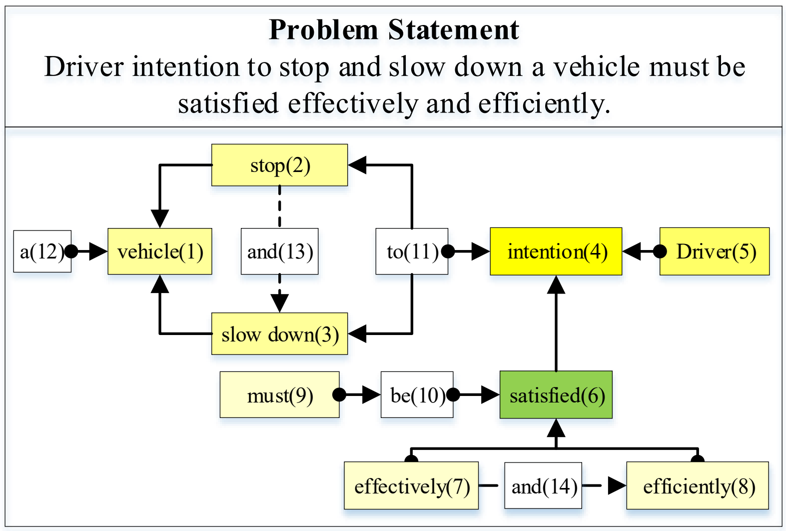


Figure 9. ROM diagram for the design statement of External Shoes braking system.

The second step in determining the solution direction is to identify the objects that need to be questioned and the sequence to question them by using the design problem statement's ROM diagram as the input. Coding the ROM diagram's objects and defining ROM diagram matrix and ranking objects according to the number of their constraints and predicate relations are activities for finding the most important object.

Table 9. ROM matrix and number of constraint and predicate relations on objects.

Object	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	**-2**	**-2**	0	0	0	0	0	0	0	0	0	0	0
2	**2**	0	0	0	0	0	0	0	0	0	**-2**	0	**1**	0
3	**2**	0	0	0	0	0	0	0	0	0	**-2**	0	**1**	0
4	0	0	0	0	0	**-2**	0	0	0	0	0	0	0	0
5	0	0	0	**3**	0	0	0	0	0	0	0	0	0	0
6	0	0	0	**2**	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	**3**	0	0	0	0	0	0	0	**1**
8	0	0	0	0	0	**3**	0	0	0	0	0	0	0	**1**
9	0	0	0	0	0	0	0	0	0	**3**	0	0	0	0
10	0	0	0	0	0	**3**	0	0	0	0	0	0	0	0
11	0	**2**	**2**	**3**	0	0	0	0	0	0	0	0	0	0
12	**3**	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0

)a)

Number of relations	4	3	2	1	0
Object	6	4, 1	2, 3, 11	10	5, 7, 8, 9, 12
Sequence to question objects	5, (5, 4), 1, 2, 3, (7, 8, 6)				

(b)

According to the definition of ROM diagram's core, "satisfied" is the core of aforementioned ROM diagram and we must perform asking question about "intention", "effectively" and "efficiently", which are constraints or predictors of the core. In order to clarify "intention", we need to ask questions about its constraints or predictors, which are "deriver", "stop" and "slowdown". Finally, the "stop" and "slowdown" also have "vehicle" as their predictor. Hence, the ranking of objects in the questioning list is as it is mentioned in

Table **9**.(b).

The third step for asking design questions is to generate questions. There is a sample question template, which we utilize it to generate questions for an identified object. Table **10** discusses the generated questions.

Table 10. ROM. Right questions for External Shoes braking system.

Orders	Questions
1	Who is driver?
2	What is driver's intention?
3	What is vehicle?
4	How/When/Why to stop and slow down vehicle?
5	What does effectively mean?
6	What does efficiently mean?
7	How does the driver's intention must be satisfied?

2. Answering the Design Questions

The design problem can be formulated with respect to the product environment (Zeng 2004b). We partition environment of a product into 3 categories, which are natural, built and human environments. On the other hand, time or sequence of activities is another dimension for product environment. In order to provide guidance to answer the design related questions, we classify environments of design problem for any important sequence of activities. Stopping and slowing down the vehicle include a sequence of activities and the environments are classified for them in Figure 10.

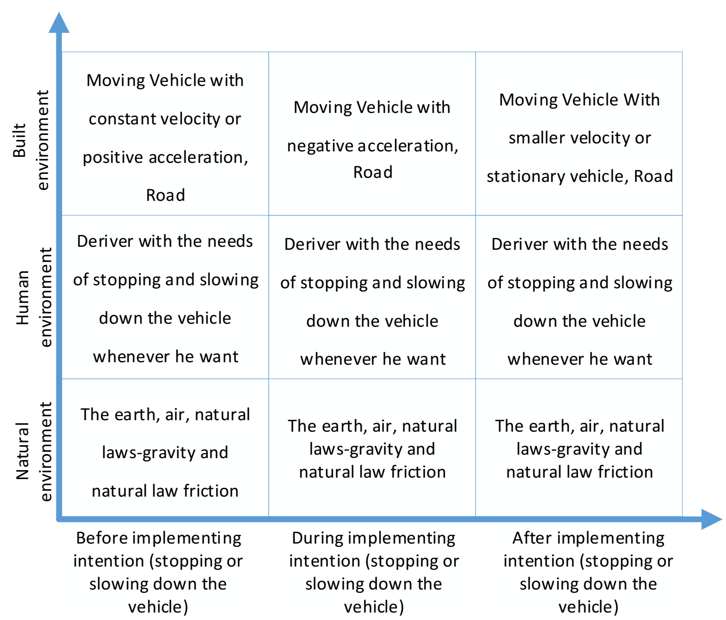


Figure 10. Life cycle of “driver intention” versus different environment component.

Classifying the environments helps us to have more information about design problem and based on this information, we answer the aforementioned design questions. In this stage, we just answer the questions, which add more helpful information. Table **11** represents design questions and their answers.

Table 11. ROM. Right questions and answers for External Shoes braking system.

Right Questions	Answers
Who is driver?	Driver control the vehicle.
What is driver’s intention?	Driver intention is to stop and slow down vehicle whenever he wants and within a short distance.
What is vehicle?	Vehicle transport people and goods.
How/When to stop and slow down vehicle?	There should be a deceleration force to stop or slow down the vehicle. Vehicle must be stop and slow down at any time.
What does effectively mean?	Effectively means that the driver can stop or slow down the vehicle whenever he wants.
What does efficiently mean?	Efficiently means that driver can stop or slow down the vehicle within a short distance.
How does the driver’s intention must be satisfied?	There should be a deceleration force which is applied to vehicle, to slow down and to stop it.

Information elicited from Right Questions and Answering analysis, is added to the current ROM diagram for further analysis. Figure 11 shows the expansion of ROM diagram.

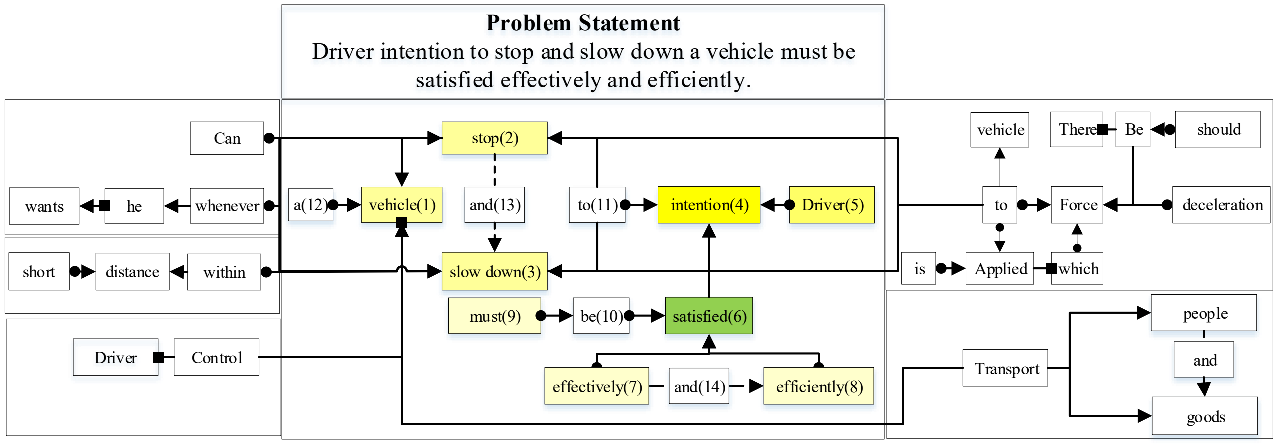


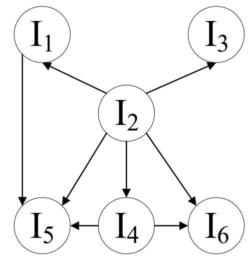
Figure 11. Extended ROM diagram for External Shoes braking system requirement.

3. Formulating Product-Environment System (PES)

The PES embodies all of the information available at a design stage including interactions between objects. Interaction dependency network is considered as the output of environment analysis. Cause and Effect analysis tries to understand relations between different interactions in the ROM diagram. We define Interaction (I) as a relation from one object to another object, which includes an action verb. We also describe that I_i has relation with I_j, if the presence of I_i causes to the presence of I_j. We identify four Interactions in the ROM diagram of External Shoe braking system, including I_1: Stop and slow down the vehicle, I_2: Apply deacceleration force, I_3:Satisfy driver intention and I_4:Whenever driver wants. Afterward, we conduct Cause and Effect analysis in order to identify Interaction Dependency Network. Figure 12 represents the Interactions and their Dependency Network.

Cause/Effect	I_1	I_2	I_3	I_4	I_5	I_6
I_1	0	0	0	0	1	0
I_2	1	1	1	1	1	1
I_3	0	0	0	0	0	0
I_4	0	0	0	0	1	1
I_5	0	0	0	0	0	0
I_6	0	0	0	0	0	0

(a) Cause and Effect table



(b) Interaction Dependency Network

Figure 12. Cause and Effect tables and Interaction Dependency Network for External Shoes braking system.

2.1.2.2. Conflict Identification

Conflicts are the driving force of product evolution in EBD analysis. Conflict identification starts with analysing Interaction Dependency Network and followed by Environment Components' Interactions analysis. In the Interaction Dependency Network, the interactions that have same resources can be sources for the reactive conflict. Also, the active conflict can happen if there is an effect without any cause.

After analysing Interaction Dependency Network, we conclude that I_1, I_2 and I_4 are probably the sources of reactive conflict or I_3 cannot accommodate enough resources for them. On the other hand, I_3 can also be source of active conflict because there is no cause for its presence. The analysed Interaction Dependency Network is discussed in Figure 13.

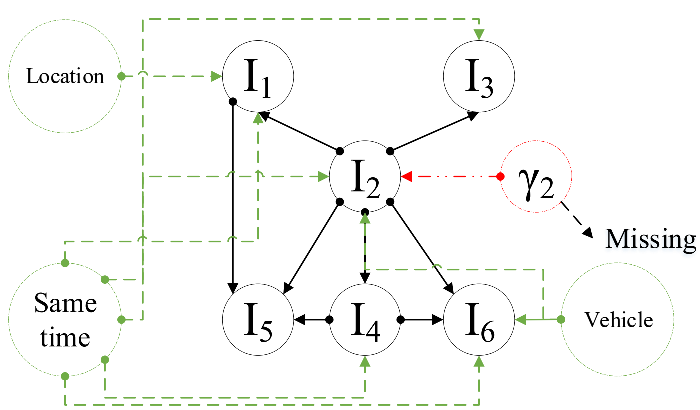


Figure 13. Cause and effect diagram for External Shoes braking system.

Analysing Interaction Dependency Network helps designers to have a good idea about sources of conflict but detailed descriptions of a conflict are obtained through Environments' Components Interaction analysis. In order to perform Environment Components' Interactions analysis, we utilize outputs of Life Cycle analysis. The interactions between these environments' components are studied to find details of conflicts.

The main purpose of Environment's Components' Interaction analysis is to study interaction of environment components, which are related to I_1, I_2 and I_4. We try to understand how I_1, I_2 and I_4 cause a conflict when I_3 does not have any resource. Air-Vehicle, Earth-Vehicle, the Earth-Vehicle, the Earth-Road, Driver-Vehicle and Natural Laws-Vehicle are all of environment components interactions. We describe each of aforementioned environment's components interactions as follows.

1. The Air-Vehicle: The vehicle is surrounded by air and the air drags the vehicle.
2. The Earth-Vehicle: The earth is the source of gravity force which acts on the vehicle.
3. The Earth-Road: The road stays on the earth and the earth supports the road.
4. Road-Vehicle: There is friction between the vehicle's wheels and road. Moreover, the vehicle runs on the road and road upholds the vehicle (wheels).
5. Driver-Vehicle: The driver operates the vehicle.
6. Natural Laws-Vehicle: Natural Law-Friction and Natural Law-gravity can act on vehicle as the sources of deceleration and acceleration respectively.

The Air-Vehicle, the Earth-Vehicle, Road-Vehicle and Natural Laws-Vehicle are the environment components interactions, which relate to I_1 and I_2. On the other hand Driver-Vehicle interaction is coupled withI_4. An abundance portion of aforementioned interactions is related to forces that are implemented to the vehicle. Hence, we describe details of the environments’ components interaction through a force analysis for the vehicle.

According to Newton’s first law, force is an influence that may cause a body to accelerate, deaccelerate and change its current motion condition. All forces including friction force, weight force and drag force, which act on a sample vehicle are represented in Figure 14. We also consider that there is an unlevelled road, which the vehicle runs on it.

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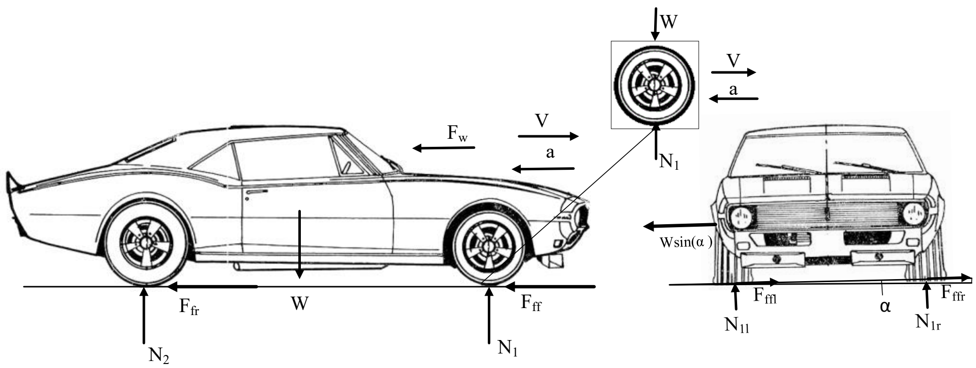


Figure 14: Interaction of vehicle with its natural law environment.

Considering that I_1 represents needs of stopping and slowing down the vehicle and I_4 express intention of driver to stop vehicle whenever he wants, we perform force analysis with respect to duration or distance for vehicle to stop.

We calculate stopping distance for a simple motor vehicle without the braking system when the driver decides to stop the vehicle and loses the accelerator pedal. In order to calculate this distance we utilize Newton’s first law and we find deceleration rate of vehicle in the absence of motor vehicle power. We derive Equation 4 from newton’s first law when $\overrightarrow{F_f}$, $\overrightarrow{F_A}$, $\overrightarrow{F_S}$ and $\overrightarrow{F_I}$ represent the friction force, the drag force, the weight force and the inertia force respectively.

$$\left(\overrightarrow{F_{ff}} + \overrightarrow{F_{rf}}\right)\overrightarrow{F_A} + \overrightarrow{F_S} - \overrightarrow{F_I} = 0 \qquad (4)$$

Considering that $\overrightarrow{F_f} = \overrightarrow{F_{ff}} + \overrightarrow{F_{rf}}$ and $\overrightarrow{F_I} = m\vec{a} = \frac{w}{g}\vec{a}$, we calculate decelerate of the vehicle from Equation 5.

$$\vec{a} = \frac{1}{m}(\overrightarrow{F_A} + \overrightarrow{F_S} + \overrightarrow{F_F}) \quad (5)$$

We assume that the air drag is negligible ($\overrightarrow{F_A} = \vec{0}$) and we have a non-level road. Hence, Equation 3 is simplified to Equation 6 and 7.

$$\overrightarrow{a_x} = \frac{1}{m}\overrightarrow{F_{Fx}} = \frac{g}{w}.\mu w = \mu g\,\hat{\imath} \quad (6)$$

$$\overrightarrow{a_y} = \frac{1}{m}\left(w\,Sin(\alpha) - \overrightarrow{F_{Fy}}\right) = (Sin(\alpha) - \mu\,Cos(\alpha))g\,\hat{\jmath} \quad (7)$$

Stopping distance is found more than 100 meters for a logical value of friction coefficient (μ) and road slope (α) and considering small amount of 5 m/s for initial velocity (V_0) in the Equation 6. This means the driver must lose the gas pedal more than 100 meters before the destination to stop the vehicle, which is not an effective and efficient way to satisfy driver intention.

$$S = \left(V_0 * t + \frac{1}{2}at^2\right) \quad (8)$$

Therefore, intention of driver to “stop or slow down the vehicle whenever he wants” cannot be satisfied effectively and efficiently. This is considered as a conflict with the aforementioned requirement, which we starts EBD analysis with it.

2.1.2.3. Solution Generation

Identifying the conflict in design process is necessary but it is not enough for product evolution analysis. In the next step, EBD must be capable of deriving the problem’s solution. EBD utilizes Asking Right Questions and Answering tool to find a possible solution for the problem. In order to resolve the conflict, we add a new system to the current vehicle for decreasing vehicle speed. We perform Asking Right Question and Answering analysis to identify more details about the aforementioned system and we call this system, the braking system as it was called in its invention time. Figure **15** depicts the ROM diagram which is elicited from second round of Asking Right Questions and Answering analysis.

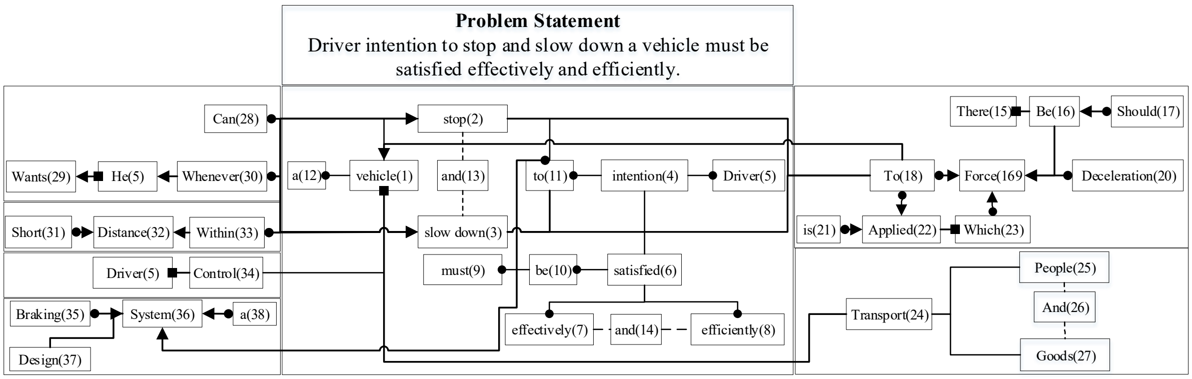


Figure 15. ROM diagram for External Shoe brake system.

In order to generate conceptual design for braking system including hierarchy of subsystems' and components' black boxes, we utilize the Asking Right Questions and Answering tool for the third time. Hence, we use ROM diagram matrix and ranking objects to extract main object for asking Right Question and Answering. Table **12** represents results of ROM diagram matrix and ranking analyses.

Table 12. ROM matrix and number of constraint and predicate relations on objects.

Object	1	2	3	4	5	6	**…**	33	34	35	36	37	38
1	0	**-2**	**-2**	0	0	0	**…**	0	**-4**	0	0	0	0
2	2	0	0	0	0	0	**…**	0	0	0	0	0	0
3	2	0	0	0	0	0	**…**	0	0	0	0	0	0
4	0	0	0	0	0	**-2**	**…**	0	0	0	0	0	0
5	0	0	0	**3**	0	0	**…**	0	**4**	0	0	0	0
6	0	0	0	**2**	0	0	**…**	0	0	0	0	0	0
…	**…**	**…**	**…**	**…**	**…**	**…**	**…**	**…**	**…**	**…**	**…**	**…**	**…**
33	0	3	3	0	0	0	**…**		0	0	0	0	0
34	**4**	0	0	0	**-4**	0	**…**	0	0	0	0	0	0
35	0	0	0	0	0	0	**…**	0	0	0	**3**	0	0
36	0	0	0	0	0	0	**…**	0	0	0	0	**-4**	0
37	0	0	0	0	0	0	**…**	0	0	0	**4**	0	0
38	0	0	0	0	0	0	…	0	0	0	**3**	0	0

(a)

Number of relations	7	6	4	3	2	1	0
Object	2, 3	1	6, 19	36, 24, 22, 18, 16, 11, 5, 4	34, 32, 27, 26, 25, 14, 13	37, 33, 23, 10, 8, 7	38, 31, 28, 21, 20, 17, 12, 9
Sequence to question objects	(19, 20), (22, 1), (35, 36), 37						

(b)

We must start asking question from "system" among new objects. On the other hand, "braking" is a constraint for "system". Hence, we start from "braking". Moreover, "force" is another important object according to rankings and "deceleration" is a constraint for it. Based on objects ranking analysis "whenever" and "within" are other objects for asking questions. The questions, which are asked for the aforementioned objects are presented in **Error! Reference source not found.**Table 13.

Table 13: Right questions and Answers for subsystems and components analysis of External Shoes braking system

Right Questions	Answers
How is deceleration force created?	External Shoe braking system creates deceleration force.
How is deceleration force applied to vehicle?	External Shoe braking system applied deceleration force to vehicle's tires.
How does the external shoe braking system decrease the speed of tires whenever the driver wants?	The external shoe brake system needs a mechanism which is controlled by the driver and which moves four braking shoes to rub on outsides of still rim tires.
What are the components of shoe braking system mechanism?	It includes lever which is controlled by the driver and linkages to transfer the driver's force to braking shoes. Moreover, it includes springs to bring back the braking system in its first situation when the driver releases the lever.

We consolidate the answers of Table 6 and we provide a description for subsystems and components of braking system as follows. The braking system has lever and brake shoes and they are contacted to each other through some linkages. In order to stop or slow down the vehicle, the driver should apply a specific amount of force to one side of lever which leads to moving of brake shoes and rubbing them with steel rimmed wheels. As the result of friction between wheel and brake shoes the vehicle speed is decreased or the vehicle can be stopped. We also call this braking system “External Shoe braking system” because of its external brake shoes. The External Shoe braking system black box configuration and its hierarchy of subsystems and components are discussed in Figure 16.

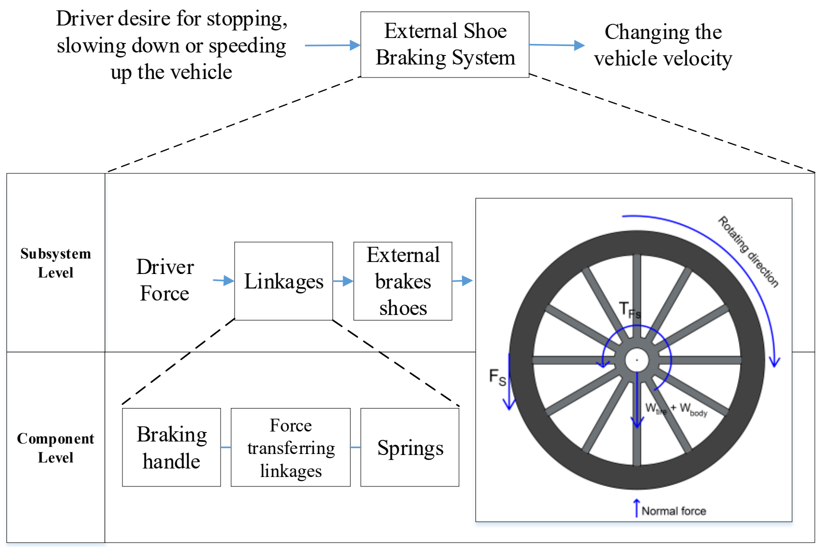


Figure 16: External shoes braking system block diagram

We analysed all braking systems by using EBD methodology through following same steps which were mentioned in this section. In the next section, we extract information from different braking systems’ requirements, conflicts and environments to conduct a trend analysis which is necessary for finding braking systems evolution’s direction.

2.1.3. Trend analysis for environment, requirements and conflicts

Predicting future of product helps manufacturers in the market competition. In order to predict future of a product, we need to know the trend of changes for product’s specifications. In our case, we try to predict future of braking system by using EBD and we define braking systems' environments, conflicts and requirements as the EBD specifications of braking systems. Hence, we are able to conduct a trend analysis for understanding potential direction of braking systems based on environments', conflicts' and requirements' changes around them.

Changing the environment around braking system is the consequence of environment components expanding. Not only a new environments' component can be added but also different aspects of an environment component can be expanded. For instance, driver needs and concerns as a component of human environment has different aspects which has been evolved during the evolution of braking systems. Different braking systems' environments and their components are presented in Table 14.

Table 14: Braking systems' environments

Braking system	**Environment evolution analysis**		
	Natural environment	**Built Environment**	**Human**
External shoe Brake system	the earth, air, natural laws (gravity-natural law friction)	Road, vehicle	driver (Stop and slow down intention), designer (problem solving), manufacturer (producing), salesman, maintenance man (preserving)
Contracting band brake system	the earth, air, natural laws (gravity-natural law friction)	road, vehicle, pneumatic rubber tires, external shoe brake system	driver (Stop and slow down intention), designer (problem solving), manufacturer (producing), salesman, maintenance man (preserving), transporter
Internal expanding shoe brake system	the earth, air, natural laws (gravity-natural law friction), rain and snow, dust	road, vehicle, pneumatic rubber tires, new material, contracting band brake system	driver (Stop and slow down intention), designer (problem solving), manufacturer (producing), salesman, maintenance man (preserving), transporter, recycle man
Hydraulic braking system	the earth, air, natural laws (gravity-natural law	road, vehicle, pneumatic rubber tires, new material, hydraulic system , internal	driver (Stop and slow down intention-comfort intention), designer (problem solving-

	friction), rain and snow, dust	expanding shoe brake system	standard), manufacturer (producing-standard), salesman, maintenance man (preserving-standard), transporter, recycle man
Power assisted braking system	the earth, air, natural laws (gravity-natural law friction), rain and snow, dust	road, vehicle, pneumatic rubber tires, new material, hydraulic system, heavy and faster vehicle, servo motor, hydraulic braking system	driver (Stop and slow down intention-comfort intention), designer (problem solving-standard), manufacturer (producing-standard), salesman, maintenance man (preserving-standard), transporter, recycle man user (needs of power)
Disc brakes system	the earth, air, natural laws (gravity-natural law friction- heat dissipating law), rain and snow, dust	road, vehicle, pneumatic rubber tires, new material, hydraulic system, heavy and faster vehicle, servo motor, new and light materials, power assisted braking system	driver (Stop and slow down intention-comfort intention), designer (problem solving-standard), manufacturer (producing-standard), salesman, maintenance man (preserving-standard), transporter, recycle man
Anti-Lock braking system	the earth, air, natural laws (gravity-natural law friction- heat dissipating law), rain and snow, dust	road, vehicle, pneumatic rubber tires, new material, hydraulic system, heavy and faster vehicle, servo motor, new and light materials, new electronic technologies, Disc brakes system	driver (Stop and slow down intention-comfort intention-safety intention during braking), designer (problem solving-standard-competition), manufacturer (producing-standard), salesman, maintenance man (preserving-standard), transporter, recycle man
VDC braking system	the earth, air, natural laws (gravity-natural law friction- heat dissipating law), rain and snow, dust	road, vehicle, pneumatic rubber tires, new material, hydraulic system, heavy and faster vehicle, servo motor, new and light materials, new electronic technologies, Anti-Lock braking system	driver (Stop and slow down intention-comfort intention-safety intention during braking- safety intention during driving), designer (problem solving-standard-competition), manufacturer (producing-standard), salesman, maintenance man (preserving-standard), transporter, recycle man

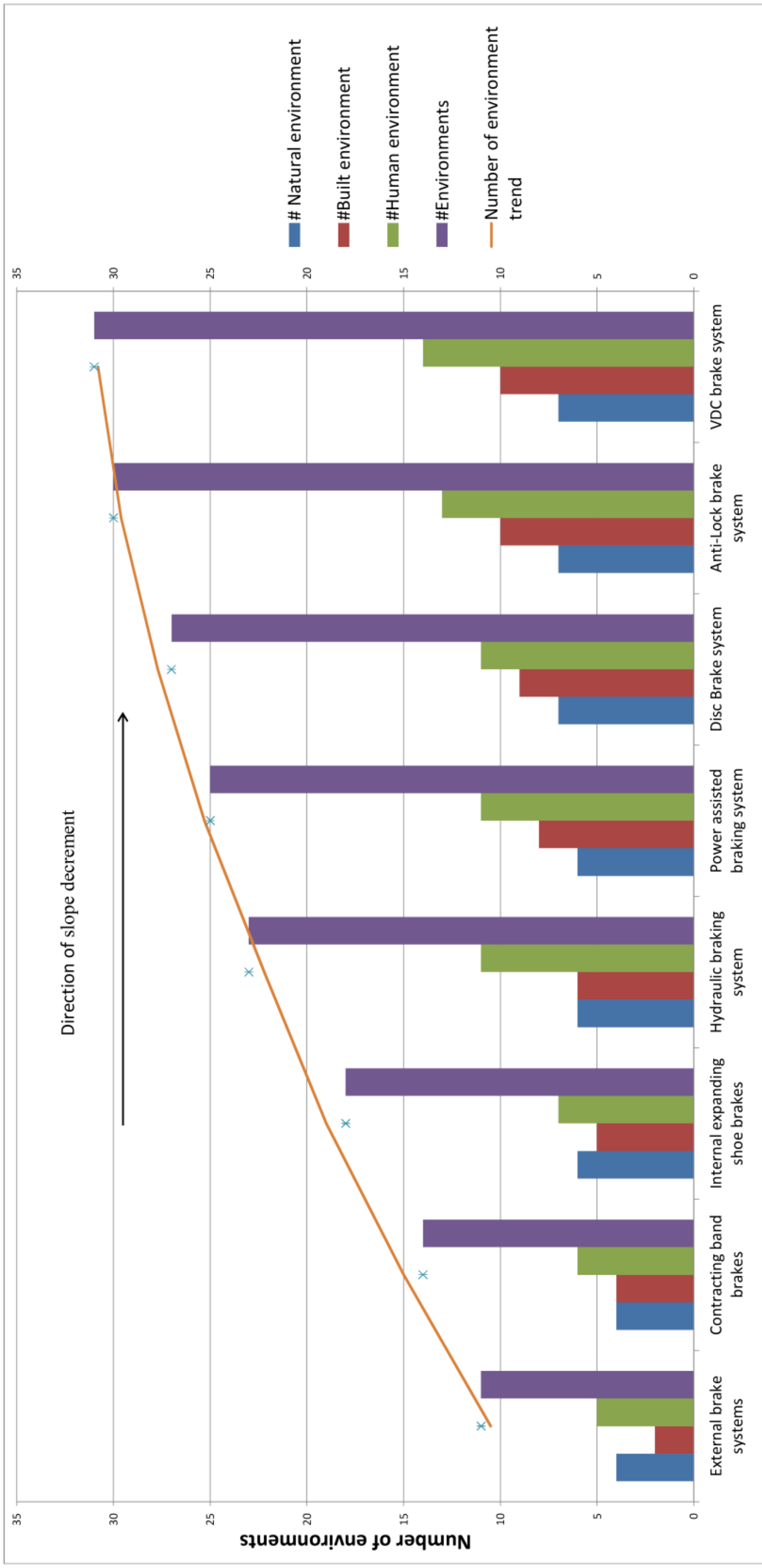
Environments are the resource for product evolution and braking systems' requirements and conflicts also change with respect to environments' changes. In other words environments accommodate conflicts and requirements. As a result, they can be utilized in the trend analysis of braking system. Considering that requirements and conflicts also have different types of Natural (N), Human (H), Built (B), Table 15 discusses braking systems' requirements, conflicts and their types.

Table 15: Braking systems conflicts and requirements

		Requirements (R)	**Types**		
		Conflicts (C)	**N**	**H**	**B**
External Shoes braking system	**R**	Driver intention to stop and slow down the vehicle must be satisfied effectively and efficiently.		✓	
	C	Driver cannot stop and slow down the vehicle whenever he wants and within a short distance.		✓	
External band braking system	**R**	Braking system must be matched with pneumatic rubber tires.			✓
	C	External shoes braking system are not suitable for pneumatic rubber tires because of the poor wear property of new rubber tires.			✓
Internal shoes braking system	**R**	In all conditions, driver intention to stop and slow down the vehicle should be satisfied effectively and efficiently.	✓		✓
	C	Braking system does not operate in the reverse direction.			✓
	C	Braking system does not work very well in the dusty, rainy and snowy climates.	✓		
Hydraulic braking system	**R**	Driver needs to operate braking system easily.		✓	
	R	Braking system must follow different types of standards.			✓
	C	Braking system does not equalize brake pressure on all the wheels and driver cannot keep braking system in a		✓	

		good operating order easily.		
	C	Designing, manufacturing and maintaining standards have not been applied to braking system		✓
Power assisted braking system	**R**	Driver needs to stop and slow down faster and heavier vehicles.	✓	
	C	Driver force is not enough to provide braking torque for stopping and slowing down the faster and heavier vehicles.	✓	
Disc braking system	**R**	New invented materials must be used to improve braking system efficiency and effectiveness.		✓
	C	Braking system cannot dissipate friction heats.		✓
	C	Braking system traps abrasive dust and water.		✓
Anti-lock braking system	**R**	Driver needs to stop and slow down the vehicle safely.	✓	
	C	Braking system cannot avoid from uncontrolled skidding of vehicle during unexpected stopping and slowing down.	✓	
	C	Braking system must stop vehicle within shorter distance.	✓	
Vehicle Dynamic Control (VDC) braking system	**R**	Driver needs to drive vehicle safely during unexpected conditions.	✓	
	C	Braking system cannot help driver to control the vehicle during unexpected situation like (oversteering or under steering).	✓	

In order to understand the trend of environments, conflicts and requirements, we plot number of different environments, conflicts and requirements for braking systems (against time) in Figure 17 and Figure 18.



Direction of slope decrement
Number of environments
External brake systems
Contracting band brakes
Internal expanding shoe brakes
Hydraulic braking system
Power assisted braking system
Disc Brake system
Anti-Lock brake system
VDC brake system
Natural environment
#Built environment
#Human environment
#Environments
Number of environment trend

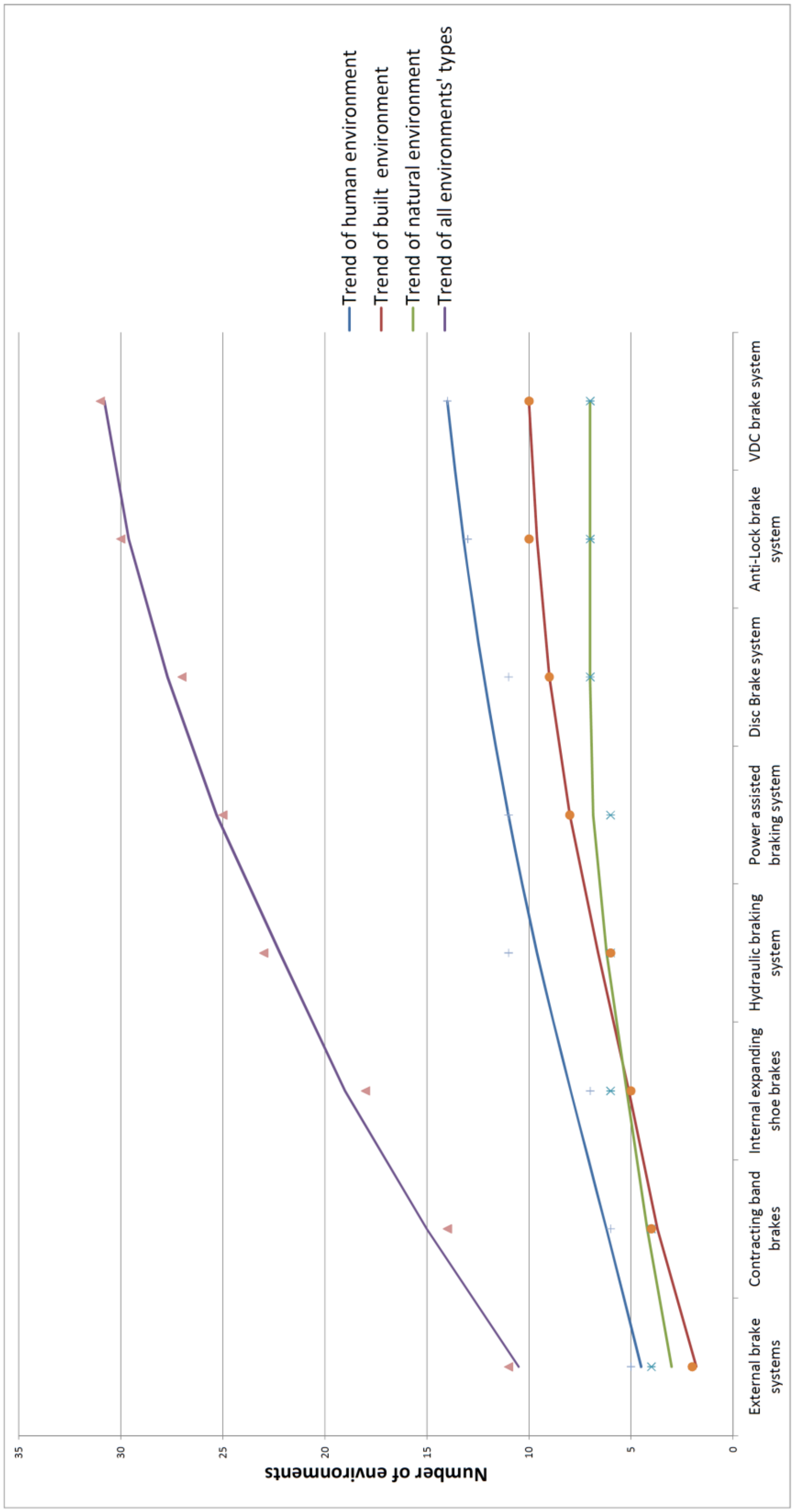
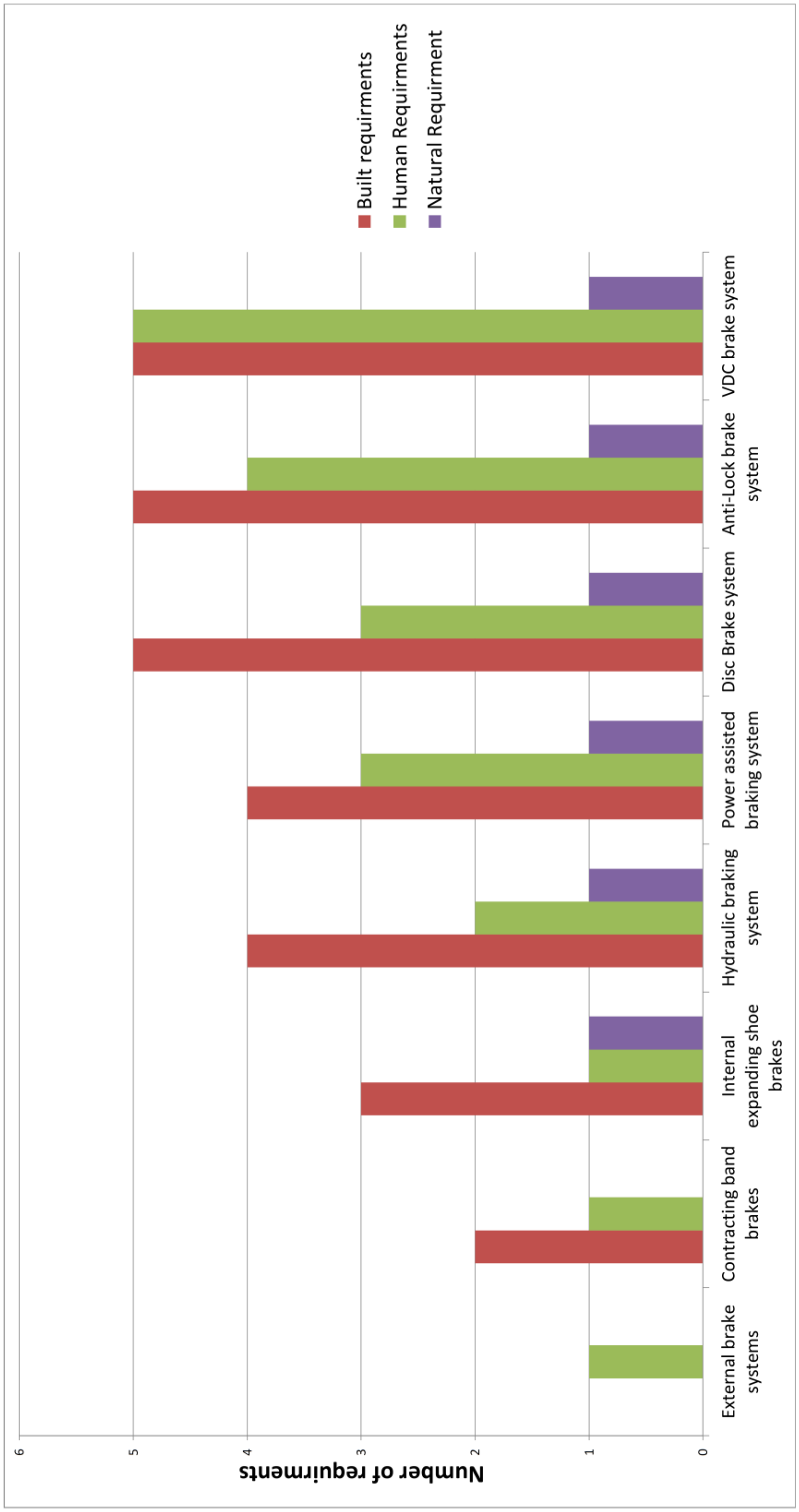
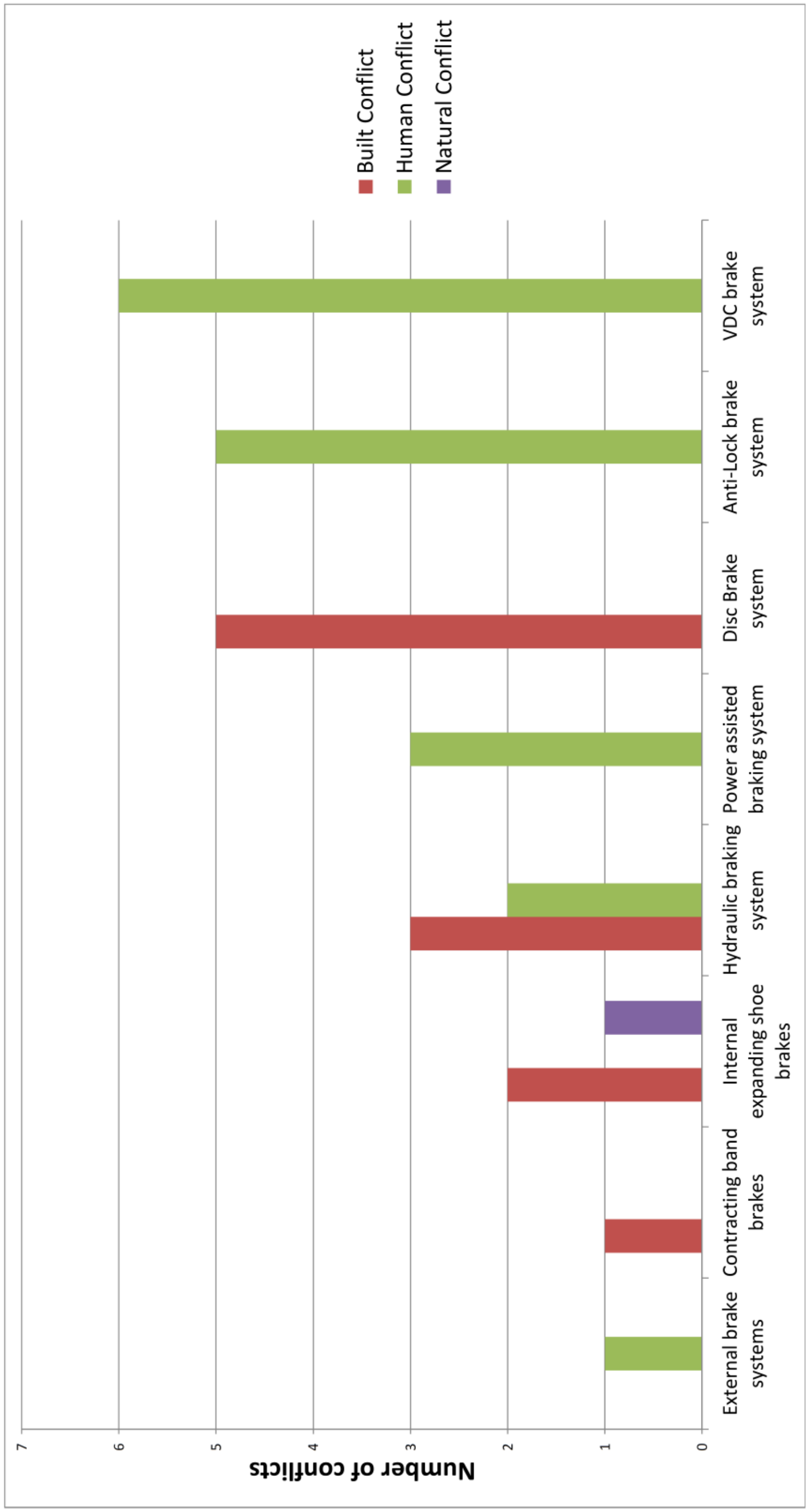


Figure 17: Trend of braking system environments' numbers and types.



Number of requirements
0
1
2
3
4
5
6
External brake systems
Contracting band brakes
Internal expanding shoe brakes
Hydraulic braking system
Power assisted braking system
Disc Brake system
Anti-Lock brake system
VDC brake system
Built requirments
Human Requirments
Natural Requirment

(a)



(b)

Figure 18: Trend of braking system Requirments (a) and Conflicts (b).

Number of environments around braking systems has been increased during evolution of them but the slope of this increment has been decreased. In other words, environments' curves are concaved down. Considering that the current slope of each curve shows its impact in the future of braking system, we compare them to find most effective environment. The current slopes of curves are about zero, thirty and sixteen degrees, for the natural, human and built environments respectively. Hence, the human environment can be considered significantly as the most effective environment around braking system in the future. There is a same scenario for requirements and conflicts and we can conclude that human requirements and conflicts are also most dominant types of requirement and conflict in the future of braking systems.

In order to conduct detailed analysis of conflicts and requirements, we define three categories of technical, safety and user-friendly for them. Drum braking system development's requirement for solving dust, rain and snow problems is the example of technical requirements. Anti-lock braking system invention's requirement, which helps the deriver to feel more comfortable, is considered as the user-friendly requirements. Finally, requirements for invention of VDC braking system, to have more control during driving is categorized in the safety group. An abundance portion of the requirements around braking systems were technical during the first stages of braking system evolution, but gradually the importance of safety and user-friendly requirements were increased. Hence, braking system should be able to cover more safety and user-friendly requirements in the future as well. Figure 19, represents trend of requirements based on the new classification.

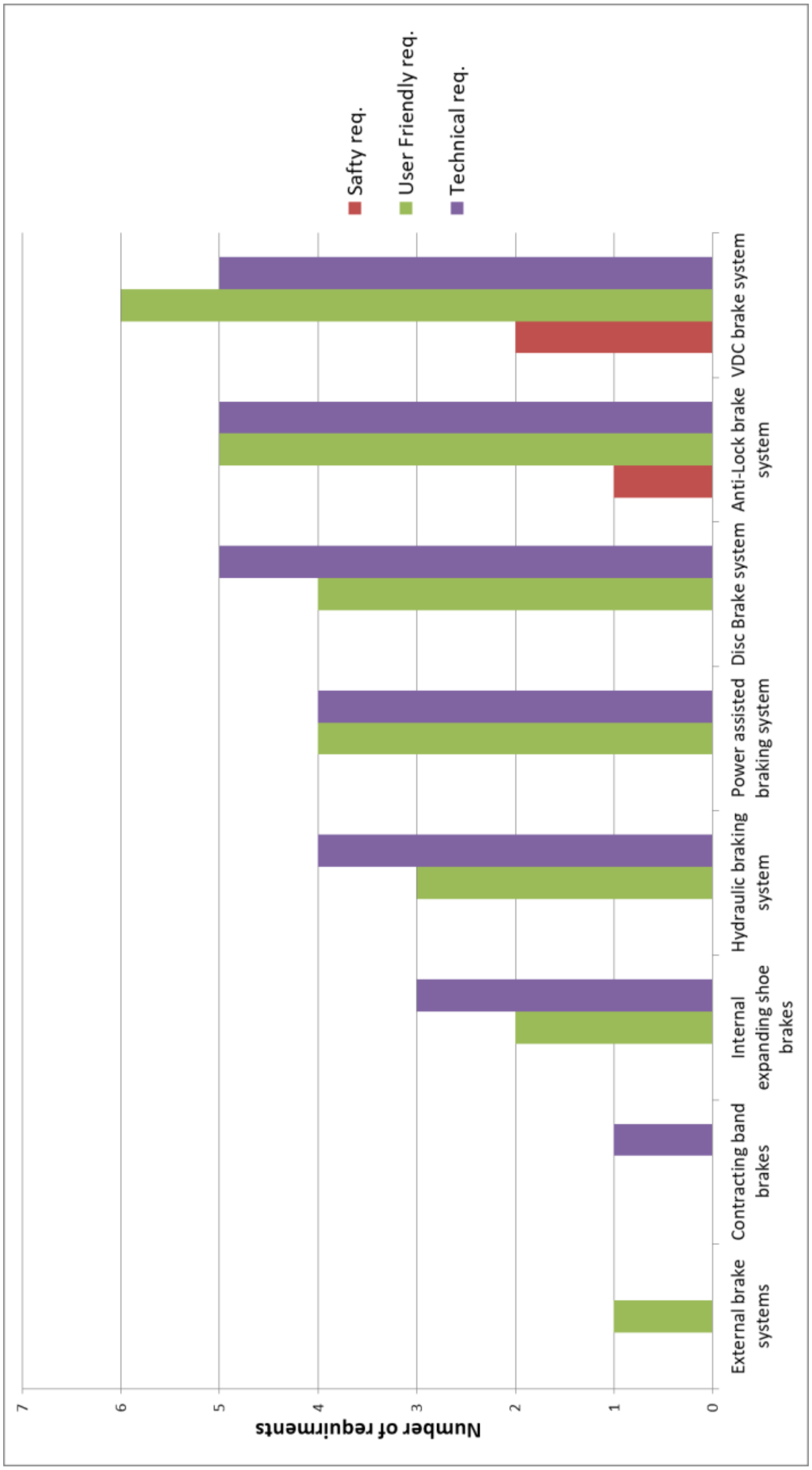


Figure 19: Number of different types of requirment for each braking system.

2.2. Prediction of next braking system generation

Number of environments around braking systems has been increased during evolution of them but the slope of this increment has been decreased. In other words, environments' curves are concaved down. Considering that the current slope of each curve shows its impact in the future of braking system, we compare them to find most effective environment. The current slopes of curves are about zero, thirty and sixteen degrees, for the natural, human and built environments respectively. Hence, the human environment can be considered significantly as the most effective environment around braking system in the future. There is a same scenario for requirements and conflicts and we can conclude that human requirements and conflicts are also most dominant types of requirement and conflict in the future of braking systems.

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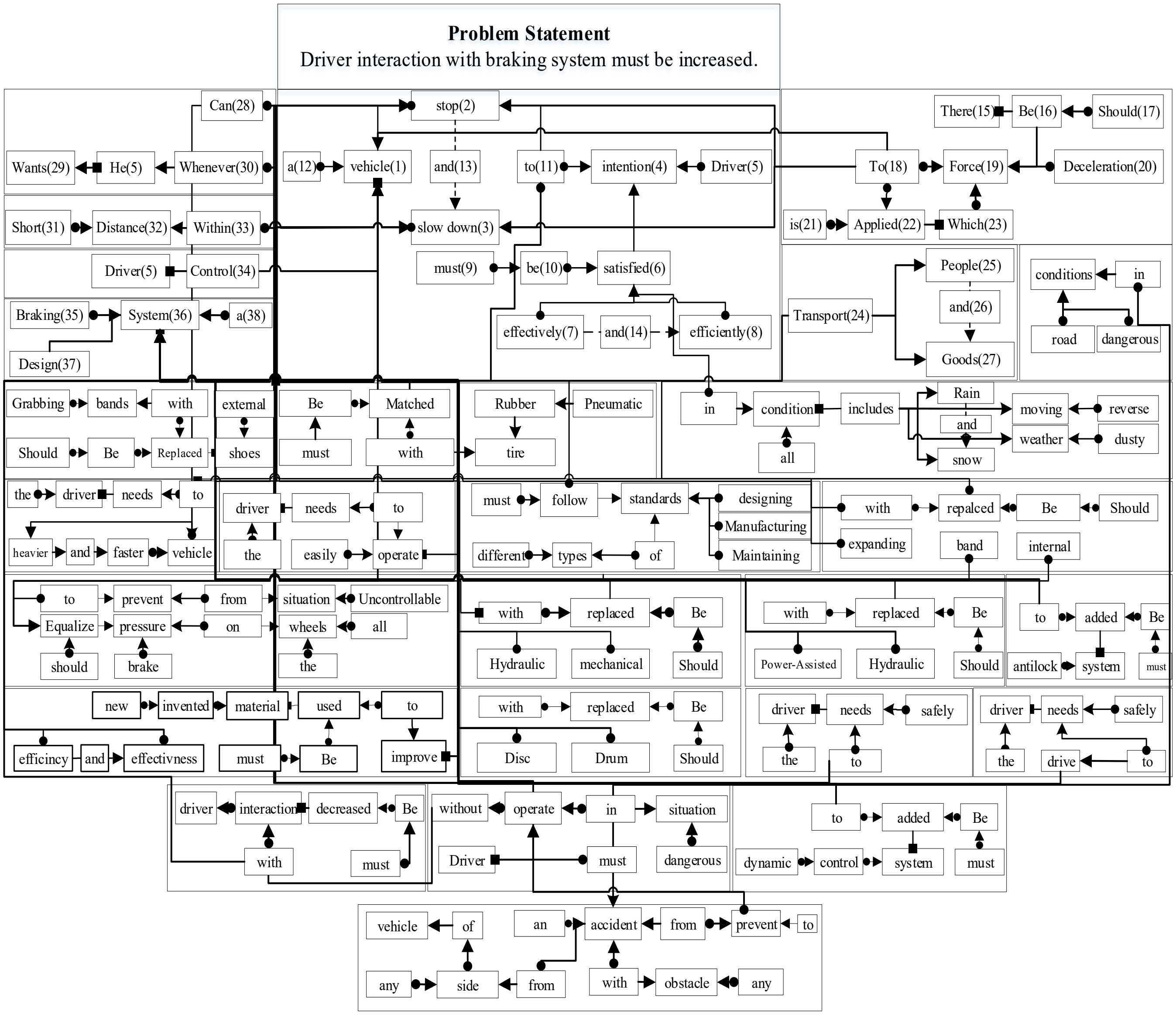
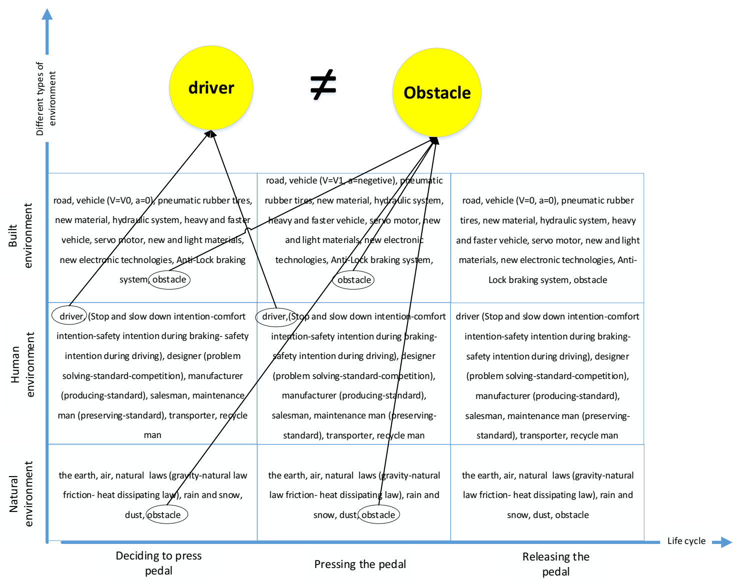


Figure 20: Rom diagram for Full Automatic braking system

We identify conflict through performing Cause and Effect analysis and Environment Components Interaction Analysis. From Cause and Effect analysis, “Automatically operation” is identified as the source of conflict. Environment Components Interaction Analysis for new components also reveals that identifying an obstacle around vehicle has conflict with decreasing driver interaction. Conflict identification results are presented in Figure 21.



I_1: decreasing the interaction. I_2: Automatically operate.

I_3: prevent from an accident.

Cause component	Effect Component	relation
I_1	I_2	0
	I_3	0

Cause component	Effect Component	relation
I_2	I_1	1
	I_3	1

Cause component	Effect Component	relation
I_3	I_1	0
	I_2	0

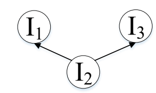


Figure 21: Cause and Effect analysis and Environment Components Interaction Analysis for Full Automatic braking system

In order to resolve the current conflict, we utilize Right Question Asking and Answering tool. New components are identified to be added to the current generation of braking system (VDC braking system). The new generation of braking system which is named Full Automatic Braking System, includes GPS and online navigation system, collision preventing sensors, line identification sensor and all components of VDC braking system. The Full Automatic braking system's block diagram is presented in Figure 22.

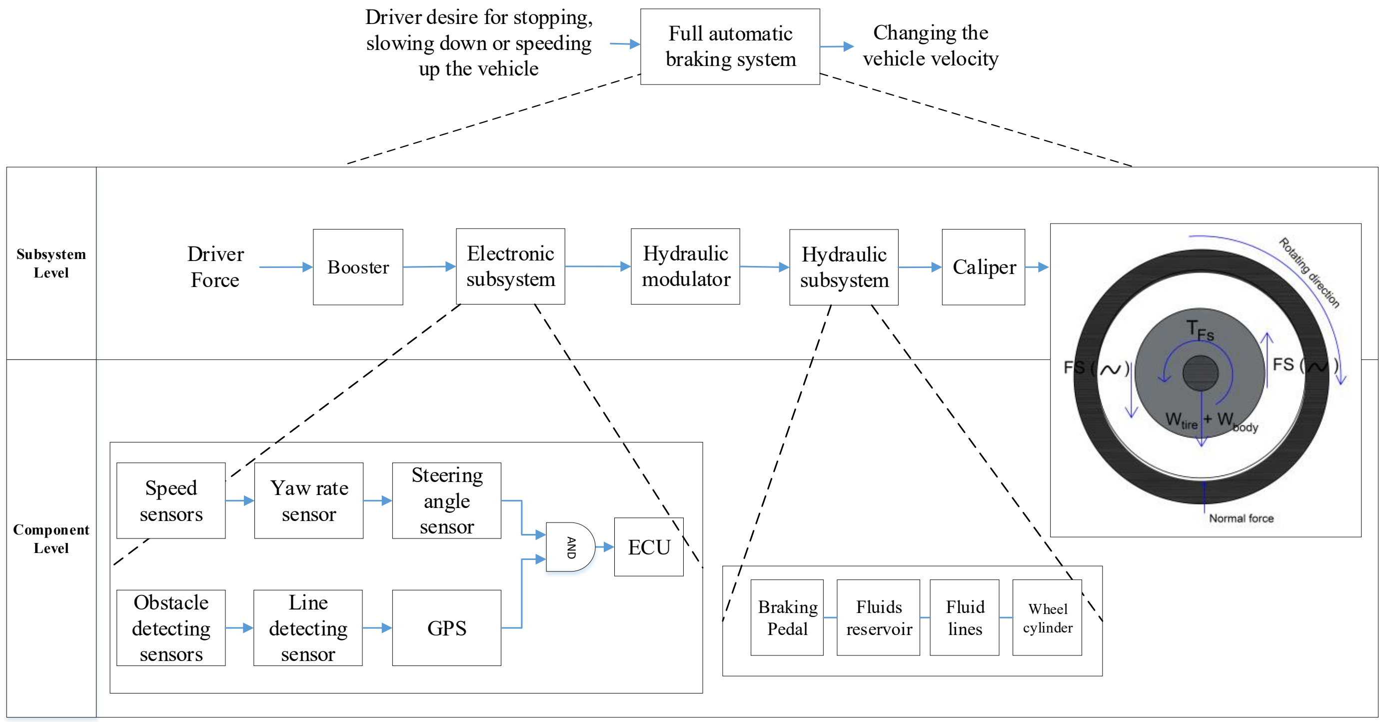


Figure 22: Full Automatic braking system block diagram

In this part of research, we presented importance of product evolution analysis and we demonstrated that a design methodology could be able to effectively and efficiently analyze product evolution, if it can be able to recognize design conflicts, design resources and design solutions. We also show that EBD is capable of product evolution analysis through conducting a case-study of braking system evolution analysis.

3. EBD Approach for Complex Systems Designing- Case-Study of Aerospace Design Methodologies

Complexity in Product Development (PD) projects emanates from many sources including product function and form, development and manufacturing process and organization structure and their relationships. Complexity can lead to uncertainty during design and development. In order to reduce uncertainty, we can identify complexities through using of systematic approach which gather, organize, integrate, and analyze the information about a project (Danilovic and Browning 2007). We follow the same procedure for the first Case-Study. ROM diagram, ROM matrix and ranking for new problem statement are presented in Figure 23 and Table 16. Based on this analysis, we must start from asking questions about “Aerospace Design Methodology”.

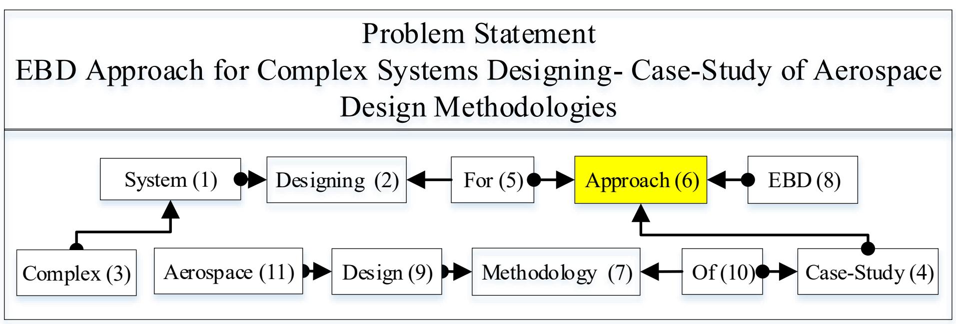


Figure 23: ROM diagram for Problem Statement: EBD approach for complex systems designing-Case-Study of aerospace design methodology.

Table 16: ROM matrix and rankings: EBD approach for complex systems designing-Case-Study of aerospace design methodology

(b)

Object	1	2	3	4	5	6	7	8	9	10	11
1	0	**3**	0	0	0	0	0	0	0	0	0
2	0	0	0	0	**-2**	0	0	0	0	0	0
3	**3**	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	**3**	0	0	0	0	0
5	0	**2**	0	0	0	**3**	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	**-2**	0
8	0	0	0	0	0	**3**	0	0	0	0	0
9	0	0	0	0	0	0	**3**	0	0	0	0
10	0	0	0	3	0	0	**2**	0	0	0	0
11	0	0	0	0	0	0	0	0	**3**	0	0

(c)

Number of relations	3	2	1
Object	6	7	1, 4, 5, 10, 9
Questioning object list	(2, 1, 3), (9, 7, 11), (8, 4)		

Aerospace products are good instances for complex product in terms of functionality, numbers of systems and components. Therefore, utilizing a good design and manufacturing methodology in aerospace industries are very important. We aim to propuse a specific design methodology for aerospace industries, which can be capable of covering all existence complexities in their development process. Therefore, we consider aerospace design methodology as a product and by analyzing environments around it, we recognize different aspects, which must be covered by the aforementioned aerospace design methodology. In order to start environment analysis for aerospace design methodology, we classify environments around it to Natural, Built and Human environments. Although, there are lots of natural rules as natural environments' components during designing of an aerospace product, we do not analyze them in top level analyses. We consider aerospace industries as the built environments for aerospace design methodology and designers and managers as human environments' components. Table 17 represents the different environments of aerospace design methodology.

Table 17: Different Environment around Aerospace Design Methodology

Different Type of Environments	Environment Around Aerospace Design Methodology
Natural	NA
Built	Aerospace Industries (current methodologies, experiences and etc.)
Human	Designers and Managers

In order to extract details of environments' components, we utilize Asking Right Question and Answering tool. We provide sequences of questions for aerospace industries and designers and mangers and we answer them. Table 18 represents output of Asking Right Question and Answering analysis for aerospace design methodologies environments' components.

Table 18: Asking Right Question and Answering for Product Evolution Analysis

Questions	**Answers**
What are aerospace industries?	Aerospace industries can be divided to military and civil industries and if we consider civil industries as the target of this research, Boeing, Airbus and Bombardier companies are the most important aerospace companies across the world. Previous experiences of these industries, their current situation and their vision can clearly represent them.
How was the previous aerospace industries experience?	In order to identify problems and sources of them during previous aircraft designing projects, we must analyze Airbus, Boeing and Bombardier projects which faced issues and difficulties.
What does help to eliminate problems and sources them during design and manufacturing?	A novel design and manufacturing methodology can help aerospace industries in preventing from occurring of any problem and issue in their products.
What are the current aerospace industries' design methodologies?	Design methodologies of Boeing, Airbus and Bombardier include their different tools and techniques must be analyzed in details.

How can current design methodologies be improved?	We try to resolve problems of current aerospace industries' design methodologies.
How does the new design methodology help designers and mangers?	A case study must be performed to identify impact of new design methodology on performance of designers and managers.

Based on the Asking Right Question and Answering analysis, we found that aerospace industries including Boeing, Airbus and Bombardier must be analyzed in details. We must analyze their previous experiences, which had problems during the development cycles in order to identify their problems and their source. Afterward, we discuss design methodologies for each of aforementioned aerospace industries to understand their advantages and disadvantages. Finally, we will be able to present a novel design methodology based on all previous experiences of aerospace industries. In order to validate any new methodology, we need to conduct a case study which needs a huge amount of research including time, budget and human resource. Hence, we postpone the case study to future researches.

3.1. Aerospace industries

Aerospace companies play a significant role in markets due to their huge amount of turnover and number of employees, and supply chain capacity. These features introduce them as hubs for many suppliers. They include the civil aviation and defense sectors, which have developed very quickly during the past few decades. These two sectors represent most top-level technologies in the world, but they still need improvement in order to deliver superior reliability and safety in their products. On the other hand, products development time and cost are very crucial in this industry due to the huge amount of budget overruns, which can be occurred for any delay in delivering the products. In order to help aerospace industries to improve, their negative experience needs to be analyzed. Afterward, we need to realize root causes of observed problems and resolve them by proposing feasible solutions.

3.1.1. Current situation of aerospace industries

In order to identify aerospace industries' place among other industries, their impacts on American, European and Canadian economies and their employment situation are analyzed in this section. Cooperation of aerospace in total Gross Domestic Product (GDP) of a country, turnover of aerospace industries, amount of job provided to society by aerospace industries and amount of investment in these industries can be good indexes for analyzing their importance. Although there are different strategic, political, military and defense intentions for aerospace industries in each country, we solely analyze aforementioned economic indexes to demonstrate situation and place of aerospace industries. US Aerospace & Defense (A&D) industry generated 1.8% US Gross Domestic Product (GDP) which is US$307B in value added products and services in 2016. In Canada, aerospace manufacturing & Aerospace Maintenance Repair and Overhaul (MRO) contribution in total GPD of country was CAD$25B which was 1.5% of Canadian GDP in 2017 and it had experienced 6% of growth during 2012 to 2017. European aerospace and defense industries called ASD also achieved a turnover of €222B in 2015 and got 11% increment compared to 2014. US A&D industries sales revenue in 2015 and 2016 was US$608B and US$872, respectively. In 2016 A&D was the second largest exporting industry in the US by exporting US$146B and generating a record trade balance of US$90B. In Canada, 75% of aerospace manufacturing products including supply chain related items (e.g. engines, avionics, landing gear, and other parts), airplanes, rotorcrafts and simulators were exported to different regions. In terms of generating jobs, US A&D industries supported 2.4 million jobs which is 13% of the nation's manufacturing workforce and 2% of the total nation's employment in 2016. Employment in European ASD and Canadian aerospace industries reached 552,625 and 190,000 employees in 2015 and 2017, respectfully. Investment of €20B in R&D section of

European ASD and average salary of US A&D employees which is 40% above the national average salary are also other factors, which demonstrate the importance of aerospace industries in different regions (Melcher 2017; Braghini, Lionneta, and D'Hollander 2016; Innovation Science and Economic Development Canada 2018). A summary of aforementioned indexes for aerospace industries in the USA, Europe and Canada are listed in Table 19.

Table 19. Contribution of aerospace industries in countries' economy in different regions (Melcher 2017; Braghini, Lionneta, and D'Hollander 2016; Innovation Science and Economic Development Canada 2018)

	GPD	Other Factors	Employment	Rate of Growth
USA	US$307B in 2016 (1.8% US GPD)	Exporting US146B and record trade balance of US$90B in 2016	2.4 million (13% manufacturing and 2% total employments)	No Information
Europe	No Information	€20B investment in R&D in 2015	190,000 in 2015	11% increment in turnover from 2014 to 2015
Canada	CAD$25B in 2017 (1.5% Canada GPD, 5% of total manufacturing GPD)	75% of products are exported	552,625 in 2015	6% and 2% of growth during 2012 to 2017 for contribution in total GPD and for employment

Considering the fact that that the aeronautic and commercial aircraft industries have a big share in A&D sectors, we aim at analyzing commercial aircraft experiences in this research research . In order to understand the importance of aerospace industries, we first analyze current situation of aerospace industries in this section. Afterward, we need to realize their visions to understand their paths in the future.

3.1.2. Visions of aerospace industries

In order to realize direction of aerospace industries, we discuss current plans of the USA, Europe and Canada for their aviation, designing processes and manufacturing processes. Americans have two different types of vision. One of them is for their aviation and another one is for their aerospace manufacturing industries. Increasing the level of safety, training skilled and dedicated workforces, advancing aviation in sustainability, using most updates technologies and increasing global collaboration are mentioned as US goals for the aviation (Federal Aviation Administration 2011). US plan for manufacturing industries is also to help small and mid-sized manufacturers, to bring industry, universities and organizations together, to use advanced materials in manufacturing. The goal is to ensure that small and high-tech businesses have access to the resources and to promote the United States as a good place for doing business. Moreover, they intend to improve their manufacturing capabilities by investing on flexible manufacturing, nanotechnologies, ultra-light materials, robotics, additive manufacturing, and other promising research areas(Materna, Mansfield, and Deck 2013). As it was mentioned above, Americans try to grow up their aerospace industries, which will have impact on wide range of manufacturers, universities and companies.Their growth is linked to more investment in the aforementioned high technologies and it will bring more business to the country.

The European vision towards aerospace industries comprises two parts: a) they try to maintain and extend industrial leadership in design, manufacturing and system integration and b) they aim to meet social & market needs in aviation until 2050. They believe that this leadership can be achieved through streamlined and upgrade processes, which address complexity of aerospace products and decrease development costs. They are also certain that prioritizing researches, needed educations and testing capabilities can help to achieve the aforementioned goals. Protecting the environment through decreasing emissions of CO2 and NOx, designing and manufacturing recyclable aircrafts, designing alternative sustainable fuels and planning emission-free taxing of aircrafts, is another goal of 2050 for Europe. On the other hand, they plan to increase and ensure safety and security for aviation and aeronautic until 2050 (Directorate-General for Research and Innovation and Directorate General for Mobility and Transport 2011).

Therefore, future of aerospace industries in Europe also has a significant impact on R&D projects, manufacturers and even Environment.

Aerospace Industries Association of Canada (AIAC) also presents Canadian visions for 2025. Being green aviation leader, keeping current market share, progressing in an innovation and export manufacturing, competing in a digital world, growing through workforce and strengthening clusters, networks and collaboration are the main goals of AIAC. They also believe that their goals can be achieved through obtaining high technologies, which are supported by world class research, testing and certification infrastructures(Aerospace Industries Association of Canada (AIAC) 2016). For instance, they try to design composite based fuselage, fuel efficient engine, integrated avionics for cockpit and critical systems and new version of landing gears (Project Management Institue 2017). As same as, American and European plans, Canadian goal for 2025 also affects researches, manufacturers and their worldwide collaborations.

Countries goals for aerospace industries beside current contribution of aerospace industries in different fields demonstrate the importance of them. Hence, effectiveness and efficiency of aerospace industries' strategies for products development are critical for countries. We analyze current design and manufacturing processes of aerospace industries, their strengths and weaknesses and we propose a novel design model in following sections.

3.1.3. Aerospace Industries Criteria

In order to analyze aerospace design methodologies and improve them, we need to comprehend criteria in designing processes of aerospace industries. We analyze different stages of a design project life cycle for an aerospace product to extract the aforementioned criteria. Moreover, a product also has a life cycle which is strongly interconnected with project life cycle. Thus, we analyze civil aviation and commercial aircrafts project stages and life cycle to identify their criteria.

A project has different steps of initiating, planning, executing, controlling and monitoring, supporting and closing. The project initiation can be expanded to feasibility study, project selection, project preinitiation and project initiation (Project Management Institue 2017). Commercial aircraft projects also follow same stages of project accomplishment. Moreover, an aircraft as a product has different life cycle steps including idea generation, idea evaluation, specification consideration, market analysis, strategic analysis, design, manufacturing, components assembly, systems , flight , market testing, maintenance and disposal. In order to elicit criteria of aerospace industries for commercial aircraft designing, we need to find relationships between different stages of aircraft life cycle and different steps of aircraft project and analyze them in detail. Table 20 presents relationship between different stages of an aircraft life cycle and different steps of its project (Markish 2002; William Spitz et al. 2001).

Table 20. Aircraft life cycle and aircraft designing project interrelations

Project steps	Aircraft Life cycle stages
Feasibility Study	Idea generation, Idea evaluation, Specification Consideration, Early Configuration and Market Analysis
Technical, Marketing, Resource, operational, schedule and financial feasibility studies	
Project Selection	Strategic Analysis
SWOT analysis, Weighting scoring method, NPV, ROI and Payback analysis	
Project-Preinitiation	Strategic Analysis
Business plan developing	
Project Initiation	Strategic Analysis
Stakeholder management, project charter development, kick off meeting holding	
Project Planning and Execution	Design, Fabrication, Assembly Components or Systems Testing
Human resource management, scope management, Quality management, Cost management, Procurement management, Risk	

management, Project progress report	
Monitoring and Controlling Phase	Flight Test, Market Test and Evaluation
Quality Assurance (QA), Quality Control (QC), Risk monitoring and controlling, Procurement monitoring and controlling, Cost monitoring and controlling, Time monitoring and controlling	
Support Service	Maintenance
Closing	Disposal
Reuse, Remanufacture, Recycle, Combustion, Landfill	

In order to realize criteria which are important for aerospace industries, we discuss in detail some concerns which must be measured by industries in each stage of project and we will conclude criteria of aerospace industries for commercial aircraft designing project accordingly. Feasibility study outputs are very early design specifications for project execution phase and main materials to prepare the business case. Therefore, specific plan must be provided to well recognize these outputs. In the project initiation, discussions should be started with airlines which know their requirements (Mutty 1993) and aircraft producers should have specific plan for emerging of new competitors, Mergers and Acquisitions (M&As) and partnership (Ecorys research and Consulting 2009; Maiti 2017a). Therefore, preparing a logical project charter and contracts to prevent it from future failures is the critical point in this phase.

Aerospace industries' organization including their size and capacity and their regional partners distribution patterns are key factors in the planning and execution phase(Ecorys research and Consulting 2009). Relying on the technology which are well understood, preventing from customer involvement in the detailed design and decision makings (Mutty 1993), managing the supply chain and manufacturing, and having effective and efficient design process are other criteria during planning and execution phase (Maiti 2017b; Malm 2013; WCIR 2013).

In the scope management, the R&D scheme of a company and efficient matching of different departments capacities are very crucial (Braghini, Lionneta, and D'Hollander 2016; Innovation Science and Economic Development Canada 2018). Handling the aging and shrinking workforce, predicting fluctuation in international currencies, time management for reducing design time cycle (William Spitz et al. 2001)and stakeholder management for having access to government financial support are examples of other noteworthy criteria during planning and execution phase. Having systematic design process during execution phase can also guarantee achieving of detailed goals such as reducing noise, NOX and CO2 (Kousoulidou and Lonza 2016). Managing different configurations for maintenance, resources, materials and spare parts and managing data and information for maintenance are also among criteria to be considered during product support service phase (Samaranayake 2006; Vianna 2009).

Compliance to the wide range of regulations, restrictions and standards for both designing and managing brings wide range of criteria for aerospace manufacturers (Maiti 2017a). European Aviation Safety Agency (EASA) and Federal Aviation Administration (FAA) are European and American agencies for authorizing civil aircrafts and regulating all aspects of civil aviation. According to EASA regulations, an airplane must follow specific standards and criteria for different systems as it is demonstrated in Figure 24. On the other hand, AS9100 standard as a cooperative effort of the International Aerospace Quality Group, covers the managements criteria for aerospace industries. AS9100 provides basic standards for configuration management, design, verification and validation phase, reliability, availability and maintainability, supplier control, verification of purchased product, product realization, traceability analysis, risk management etc. (SAE Aerospace 1999).

Considering aforementioned concerns and criteria we can realize that planning and managing early design specification, competitors and partners, customer, stakeholder and resources (human), having systematic design process, and managing and scheduling maintenance processes are the main concerns and criteria of aerospace industries which are dependent on industries' design and management methodologies. Hence, having systematic and efficient design, manufacturing and management methodologies are most important challenges, thus we must first analyze their current design, manufacturing and management methodologies to realize their advantages and disadvantages.

Figure 24: EASA criteria categories and sub-categories

3.2. Previous Aerospace Industries' Experience and Their Problems

In order to realize and resolving current problems in aerospace industries' design methodologies, we need to analyze their previous experiences and their design methodologies. Boeing, Airbus and Bombardier are well-known as pioneers of civil aerospace industries. Hence, we study projects' indexes including their duration and cost and the problems occurred during projects execution for some of their projects. In order to analyze different types of aircrafts, we consider A380, B787 and Bombardier CSeries to provide cases for large, medium and small size aircrafts, respectively.

Considering SE process as the main model for designing complex product, increasing level of SE implementation in aircraft designing leads to better quality of design and decreases design problems. In order to achieve deep understanding about problems and their sources in each of projects, we need to analyze the level of SE implementation in A380, B787 and Bombardier CSeries projects. Therefore, we calculate level of SE implementation for each project firstly. Afterward, we analyze each project problems, sources of them and their relationship with projects design and managements methodologies. Finally, we present Boeing and Bombardier design and managements models.

3.2.1. Aircraft designing Life cycle times and costs

The Airbus A380 is a double-deck and wide-body aircraft and the world's largest passenger airliner with capacity of up to 853 passengers. The program started in June1994 and with a design cycle time of 151 months. It was planned to be delivered at the last quarter of 2005, but first aircraft was delivered in October 2007. This program had about two years delay and late delivery cost of $6B dollar (Stark 2005; Bourne 2004).

The Boeing 787 Dreamliner is an American long-haul, mid-size aircraft with a capacity of up to 335 passengers. B787 design program was started in 2003 and its design life cycle took 106 months. The first B787 was delivered in September 2011. The program cost about $40 B which includes more than $ 20 B overrun. This project has total delay of 40 months (Nelson 2005; Brook 2017; Mecham 2011).

The Bombardier CSeries is family of small size and medium-range aircraft. The capacity of CSeries is up to 133 passengers. The project started in 2004 but continued from 2007 and the product design cycle time was 107 months. The project had 3 years delay in getting aircrafts into service and at least $2 B overbudget with a program cost of $ 6 B. Figure 25 presents all of aforementioned aircraft designing projects life cycles (Son and Luong 2006; Farrar 2006).

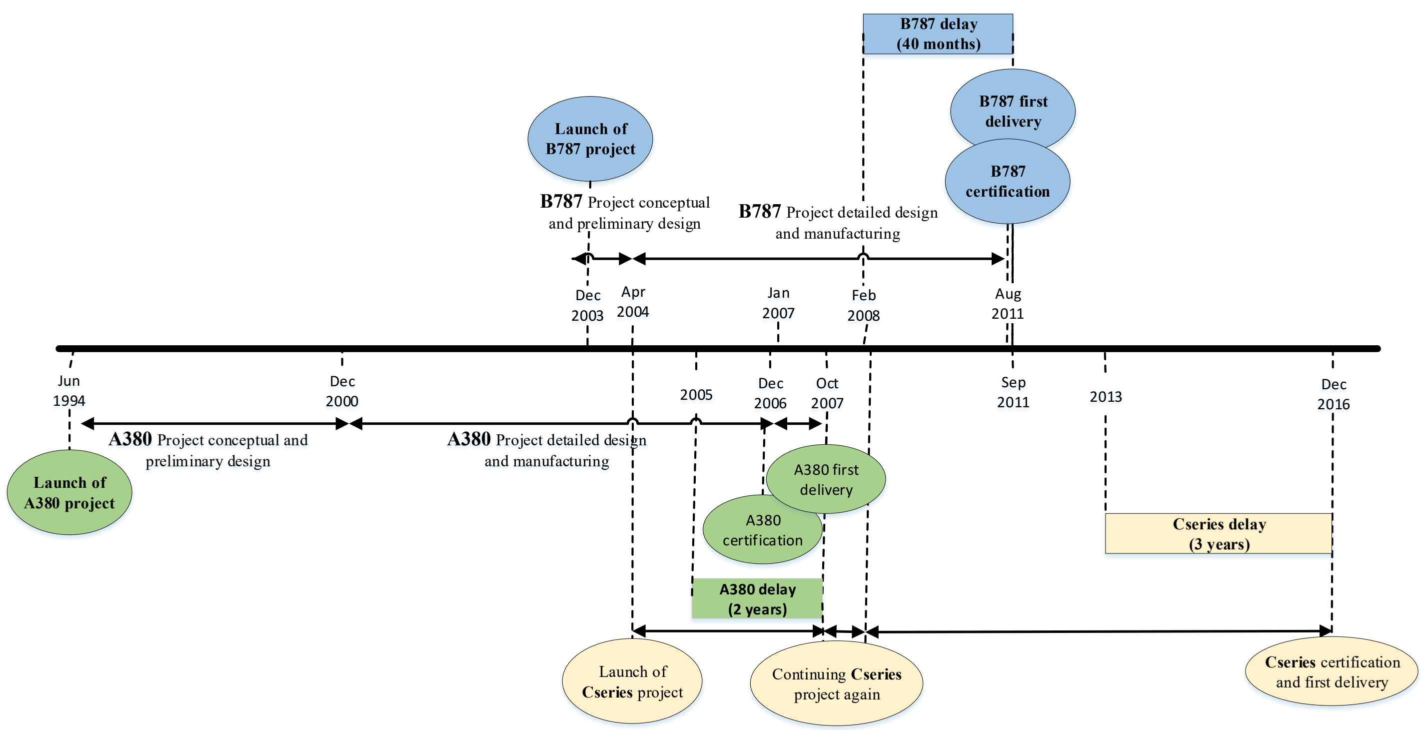
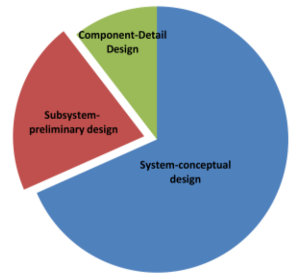


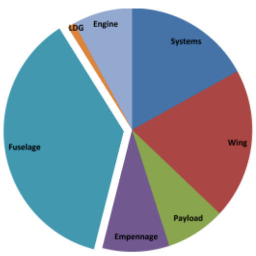
Figure 25. A380, B787 and Bombardier CSeries projects' life cycles

3.2.2. Aircraft designing experiences in implementing of System Engineering

In order to recognize total level of System Engineering implementation in each project, we need to calculate this level for each aircraft system. Therefore, we investigate implementation of SE in different levels of aircraft designing. Afterward, we need to consolidate all systems' shares in all design stages to calculate total level of SE implementation. Therefore, we need to know each system of aircraft share among whole systems and each stage of design share during project life cycle.

Aircraft can be divided to 8 major parts including systems, wings, payloads, empennage, fuselage, LDG and engine. System includes onboard systems "avionic system, fuel system flight system, hydraulic system and etc.". Payload can also be introduced by seats, bag racks, cargo equipment etc. Comparing systems' cost and different stages of design cost for companies can be good measure for systems and design stages share in whole of project. Therefore, average of non-recurring and recurring costs of each system was considered as each system share in calculations. Moreover, we consider percentage of committed costs after each phase of design as each design phase share in the calculation. For both of aircrafts, it is assumed that the feasibility study and conceptual design phases were performed inside company. Outsourced systems are considered as parts of aircraft which System Engineering (SE) was not applied to them. Levels of outsourcing for A380 and B787 are 40% and 70% of whole systems respectfully. Considering the Level of outsourcing, design phases shares and systems share, level of System Engineering for A380 and B787 are calculated 85% and 78% respectfully. Figure 26 represents design phases share; systems share and levels of System Engineering implementation for A380 (Vianna 2009; Stark 2005; Nelson 2005; Brook 2017; Mecham 2011)





			Design phases shares (%)		
			System-conceptual design	Subsystem-preliminary design	Component- Detail Design
			0.684210526	0.210526316	0.105263158
Systems shares (%)	systems	0.17	1	0.6	0.6
	wing	0.2	1	0.6	0.6
	payload	0.08	1	0.6	0.6
	empennage	0.09	1	0.6	0.6
	fuselage	0.37	1	0.6	0.6
	LDG	0.01	1	0.6	0.6
	Engine	0.08	1	0	0

Figure 26: Level of System Engineering (SE) implementation in A380's systems (Markish, 2002)

3.2.3. Sources of problems for aircraft designing experiences

Having tremendous delays and overruns are outcomes of three aircraft designing and manufacturing projects. In order to prevent occurring same problems during designing and manufacturing process in the future, we need to recognize them and find a solution for preventing them. We discuss sources of delays and malfunction for A380, B787 and Bombardier CSeries project in this section.

A380 project suffers from happening of problems including expensive and complex repair and existence of cracks around fastener holes in the internal wing structure and at the edges of vertical web of the feet. Nevertheless, the main technical reason for the projects' delays was wiring design defects. Airbus found the roots of these problems in using of different version

Computer Aided Design (CAD) software to create the engineering drawings by different design groups and consequently, stripping out the wiring from the prototype, redesigning the wiring, making new harnesses and then rethreading the wiring into the airframe became reason for delays. On the other word, decision making for using of different CAD versions resulted in design inconsistencies, mismatched calculations and configuration management failures (Bourne 2004).

B787 project confronted two types of problem, supply chain issues and safety events for in service aircrafts. Lithium batteries problems in electrical system, engine shutdowns, fuel leaks, loss of transponder, hydraulic failures, cracked windscreen, and cracks in wings are examples of B787 project safety issues. Beside all that, Boeing tried to reduce the cost of manufacturing and assembly by transferring design and manufacturing tasks to first tier supplier. Lack of management for the handling supply chain and new technology like composite was the main root cause of Boeing's struggles in B787 project. The project repeatedly experienced insufficient supplies of basic components, such as fasteners, frames, clips, brackets, and floor beams which lead to huge delay on delivery (Brook 2017; Tang, Zimmerman, and Nelson 2017; Shenhar et al. 2016).

By digging into details of Cseries project's problems, it was found out that bombardier did not consider geopolitical or financial uncertainties and risks. These kinds of risks can be considered in yellow or red risks categories and they should be analyzed carefully. As the result of the aforementioned risk happening, bombardier had lots of problem in competition with Boeing and Airbus which are the dominated company in large passenger plane market. Moreover, Bombardier also had problem with Pratt & Whitney for having delays in engine delivery. Hence, lack of risk and uncertainty management, procurement management and customers management for having more orders lead to bungled Cseries project (Team Aero 2010).

By considering all the aspects of design and manufacturing problems discussed projects, the aerospace companies should reconsider their design and management methods. Utilizing System Engineering process is not adequate for eliminating the defects in design and manufacturing of complex project. For instance, Boeing tries to improve its design and manufacturing processes by considering System of System Engineering (SSE) and Model Based System Engineering (MBSE) for having better interaction with customers and suppliers during design and manufacturing stages (Nelson 2005; Mecham 2011).

As it was discussed above, current design and manufacturing methodologies of aerospace industries need improvement. In order to resolve current disadvantages of them, we discuss methodologies of Boeing and Bombardier in the next section and afterward we propose our novel methodology.

3.2.4. Boeing methodology

Boeing as the pioneer of using System Engineering utilizes specific tools and methodologies such as Agile System Engineering in its design process. Agile System Engineering can be implemented during the first stages of design including functions and requirements identification. Moreover, a combination of Agile System Engineering and Agile Software development including different scrums, iterations and scrums' events are performed in the other stages of product development in Boeing company (Carlson and Matuzic 2010; Matuzic 2012). Project management is natural part of System Engineering in Boeing Company. In other words, project management is the canopy of umbrella and SE is ribs (Son and Luong 2006). Boeing uses

Process-Based Management includes three main stages of defining the process, analyzing the process and improving the process. It also utilizes Lean and Six-Sigma ideas for measuring the customer metrics (quality and timeliness) and business metrics (efficiency and cycle time) in its Process-Based Management (Farrar 2006).

Boeing is also a pioneer in using Model-Based Systems Engineering (MBSE) which help designer to have better decision making in comparison with document-centric approach (Pagnanelli, Sheeley, and Carson 2012; Paredis 2011). It uses quality, cost, schedule, productivity and resource as the indicators for measuring SE performance (Luong and Nguyen 2006). QFD and trade study are the other techniques which Boeing uses in combination with SE. QFD is used in all stages of design to transfer current information and data to more detailed data (TAI 2002c). Moreover, trade study has different roles including, comparing alternatives to meet customer needs in conceptual design, comparing and selecting configurations and technologies in preliminary design and comparing and selecting components and test methods in detail design and verification stages. Function analysis (TAI 2002a), requirement management and changes management (TAI 2002b) are also parts of Boeing's MBSE process. Requirement Allocation Matrix (RAM) and Requirement Verification Matrix (RVM) are Boeing's tools in Requirement management and Structured Analysis and Design Technique (SADT), information flow analysis and N2 diagram are its tools in function analysis (TAI 2002a). Summary of Boeing design and manufacturing methodology, tools and techniques are discussed in Figure 27.

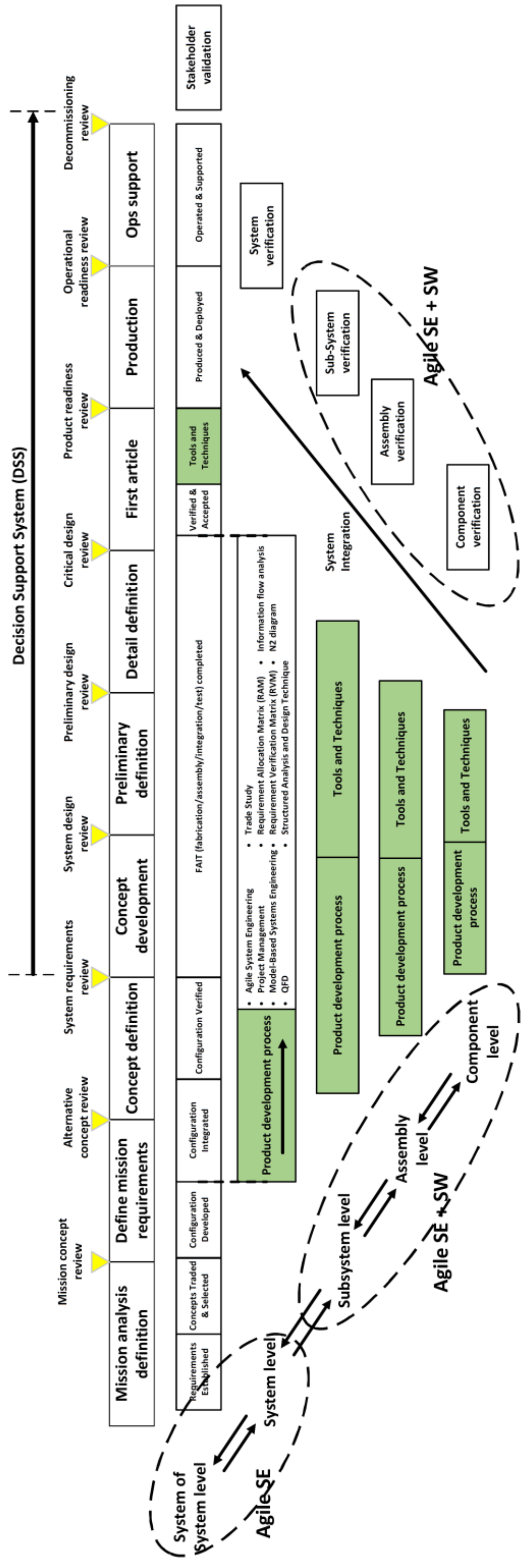


Figure 27: Boeing's design and manufacturing methodology and its tools and techniques

3.2.5. Bombardier methodology

Bombardier product development methodology (BES) is fuzzy front end. A fuzzy front end method starts with a vague idea for a new product, and ends with decision for launching a formal development project. In bombardier, managing project portfolio is a part of their fuzzy front end process. Bombardier tries to make decisions about investment, match investments to objectives, asset allocation for individuals and institutions, and balance risk against performance. Portfolio project management follows with project management.

In order to analyze bombardier project management methodologies, we need to know diverse stages of development and decision making. Product development has seven stages including conceptual definition, launch preparation, preliminary definition, detail definition, product definition release, product certification and product completion. Product development process has nine steps of review. It starts with feasibility study review and it finishes with operation validation review. All stages of Bombardier's product development and design review are presented in Figure 28.

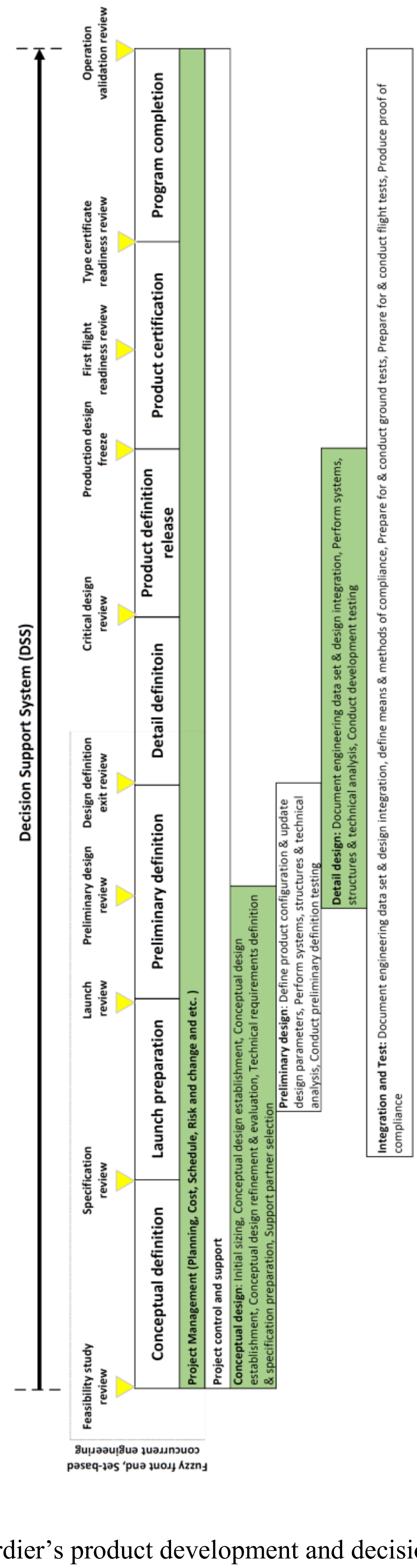


Figure 28: Bombardier’s product development and decision making stages.

3.3. Interdisciplinary Design Method

We analyzed strategic direction of aerospace industries in different regions and realized their main challenges and criteria which are the effectiveness of their design and manufacturing and their management methodologies. Afterward, we discussed previous experiences of aerospace industries and their problems and design methodologies which are utilized in their companies. In this section we aim at customizing design, manufacturing and management methodologies for proposing a powerful methodology.

3.3.1. Previous methods advantage and disadvantages

All aforementioned aerospace companies tried to utilize System Engineering (SE) in different levels in their design process. Boeing has well-structured design methodology, which includes Model-Based and Agile System Engineering, QFD, project management and trade study as main components. Although Boeing design methodology is well structured System Engineering process, utilizing combination of EBD, AHP and AD can help it with better decision making in each stage of design. Moreover, it is not clear that how project management skills and manufacturing skills are utilized in Boeing methodology. On the other hand, Bombardier utilizes a fuzzy front end methodology but SE is not fully developed in its processes. Analyzing available literatures for Boeing and Bombardier, to the best of our knowledge, demonstrates that Boeing design methodology contains more elements of SE than Bombardier. Therefore, we propose a novel design methodology based on all features of aforementioned design, manufacturing and managements methodologies in the next section.

3.3.2. Proposed design method

In order to propose a respectable model for aircraft developing project, we need to employ design and manufacturing methodologies as well as management theories to handle all complexities of these processes.

QFD is a tool for transferring requirements to design parameters in different stages of design. Therefore, QFD output in the first stage of design, which is feasibility study of a project and initiation phase, can be utilized as the input of conceptual design stage and so on so forth. Agile management helps design process when industries need to response to rapid changes. Hence, combination of Agile project management and System Engineering (SE) helps designers to have better performance in case of rapid changes. AHP is utilized as a tool for ranking different alternatives based on a number of different criteria and we can utilize AHP for ranking different inputs in each stage of design. EBD methodology is a powerful tool for expanding a situation (design problem), finding conflicts and solving them. Therefore, it can be utilized in coordination with AHP to find core aspects of design problem and solve them. Axiomatic Design (AD) theory can help designers to transfer voice of customer to design task, design task to functional requirements, functional requirement to design parameters and design parameters to process variables. Lean, Kanban and LPPD methods also can help components manufacturing, systems assembly and product assembly processes. Components verification, system verification and product validation are also parts of SE process, which are performed according to standards.

Therefore, we can propose a design process based on all aforementioned design methodologies, managements models and aircraft life cycle. If we present an aircraft life cycle by feasibility study, conceptual design, preliminary design , detailed design, component manufacturing and test, systems assembly and test and product prototype assembly and test, we can utilize QFD as a tool in each design section of life cycle for transferring inputs to outputs where AD and trade study methods help transferring processes. Outputs of conceptual, preliminary and detailed design QFD houses (Process variables, design parameters and functional requirements) are utilized as inputs for components manufacturing and systems and product assembly QFD houses. Lean, LPPD, Kanban and trade study methods also are operated in manufacturing and assembly houses for identifying manufacturing and assembly processes. In our proposed model, we utilized combination of EBD and AHP in the beginning of each QFD's house to determine details of design problems in each stage. EBD helps to clarify design problem and to find conflicts which must be solved and AHP can collaborate in ranking the design problems aspects and conflicts. Figure 29 presents the proposed design, manufacturing and management methodology along the design stages.

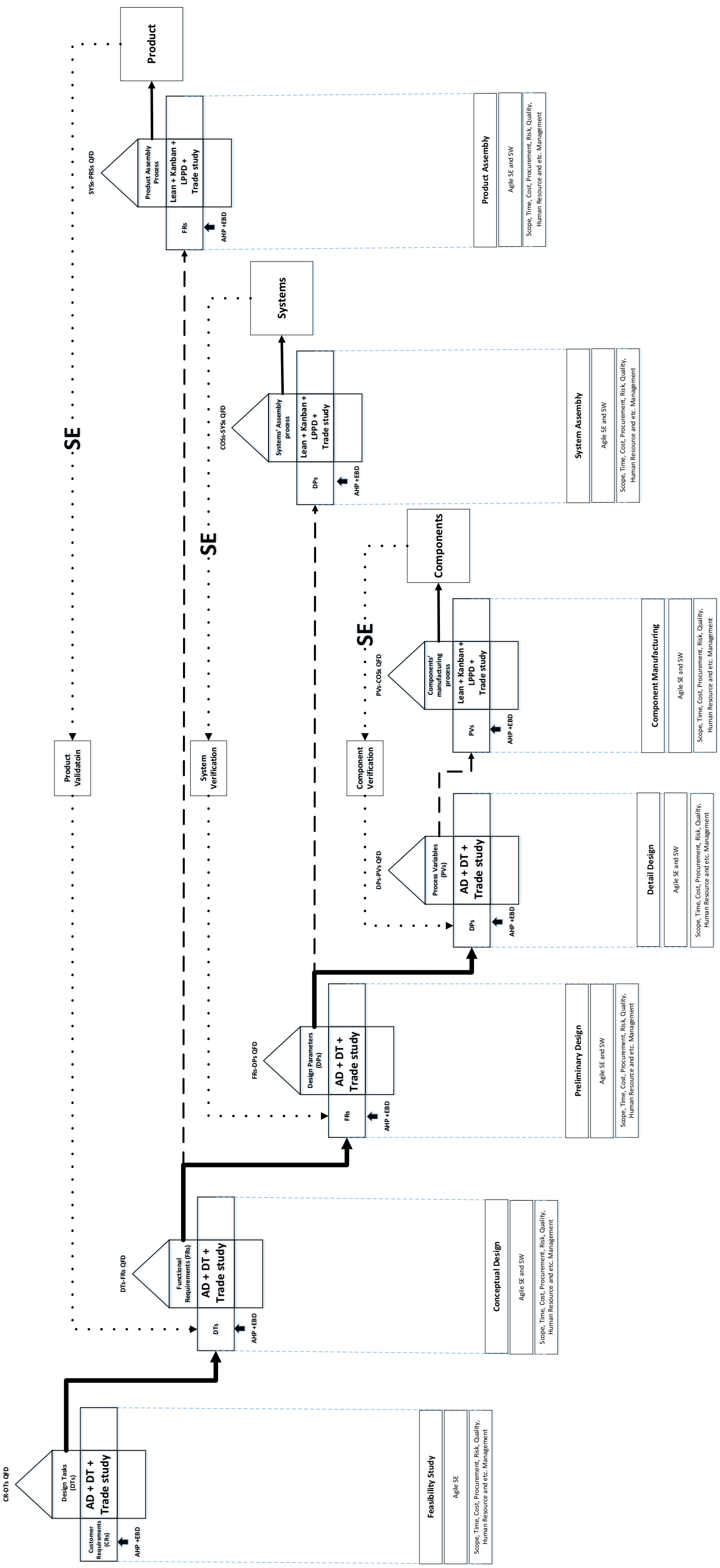


Figure 29: Design, manufacturing and management methodology for aerospace industries.

We proposed a design methodology, which is a combination of different design and management models. We conclude from previous experience of aerospace industries that the problems in their management model and design methodologies were reasons for the projects' problems. In order to manage difficulties of designing a complex product, we need to utilize all capabilities of design methodologies. Hence, the proposed design methodology combines different design methodologies and management models. SE is the basic of proposed methodology; QFD is utilized in each level of design to transfer data from previous level of design to a more detailed level; EBD and AHP help designers in clarifying problem situation in each stage of design and Lean, Kanban, Trade Study and AD are other techniques which are utilized in this methodology. This methodology constructed based on aerospace industries experiences but it can be utilized for designing any complex product and just details of designing will be different. In this section we demonstrate role of EBD in coordination with other design and management models for designing a complex product.

4. EBD Approach for Human Centric System Designing-Case Study of Course Scheduling

System is defined as a combination of interacting, interrelated or interdependence parts that work together to perform a function and form a whole. Each system has inputs and output based on the function performance. Physical and social systems are two different types of system. Any mechanical product such as telephone or any organ is classified in physical system group. Health care and education institutes are examples of social systems. Social systems also are presented as human centered systems. Academic institutes are also an example of human centered system, which have untrained and trained individuals as their inputs and outputs respectively.

We perform ROM diagram, ROM matrix and ranking analyses to identify core object of problem statement and objects, which questioning must be started from them. Figure 30 and Table 21 represent result of aforementioned analyses. According to the results of analyses, we start asking question from “course scheduling”.

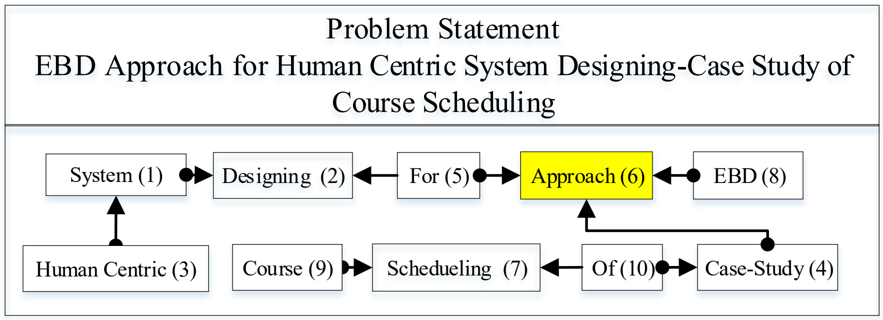


Figure 30: ROM diagram for Problem Statement: EBD approach for human centric designing- Case Study of course scheduling.

Table 21: ROM matrix and rankings EBD approach for human centric designing- Case Study of course scheduling.

(a)

Object	1	2	3	4	5	6	7	8	9	10
1	0	**3**	0	0	0	0	0	0	0	0
2	0	0	0	0	**-2**	0	0	0	0	0
3	**3**	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	**3**	0	0	0	0
5	0	**2**	0	0	0	**3**	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	**-2**
8	0	0	0	0	0	**3**	0	0	0	0
9	0	0	0	0	0	0	**3**	0	0	0
10	0	0	0	3	0	0	**2**	0	0	0

(b)

Number of relations	3	2	1
Object	6	7	1, 4, 5, 10
Questioning object list	(2, 1, 3), (9, 7), (8, 4)		

There are different concerns for academic institutes such as their schedules, which must be planned based on aforementioned individuals' needs. In this part of this research we aim at analyzing EBD application in designing of course schedules for an academic institute.

Designing academic curriculum, courses schedules, exam schedules and many other academic calendars are challenging for academic institutes due to presence of different factors in their designing process. Considering that quality of academic curriculum, courses and exams schedules can directly impact student, instructors and institutes performances, we aim to propose a new course scheduling model. If we consider course scheduling as a product, we are able to analyze different aspect of designing a new course schedule through EBD analysis. We start our analysis with extracting Natural, Built and Human environments for a course scheduling model. Natural environment includes daily duration of day which is 24 hours. University classrooms and regulations involve in Built environment and students and instructors are components of Human environment. Table 22 presents different environments around courses scheduling.

Table 22: Different Environment around Courses Scheduling

Different Types of Environments	**Environments around Course Scheduling**
Natural	Daily hours
Built	University's classrooms, University's regulations
Human	Instructors, Students

In order to understand different aspect of course scheduling process, we need to have more detailed information about its environments components. Hence, we perform the Asking Right Question and Answering analysis by asking more questions about each component of environments. Table 23 presents sequences of questions and answers for the environments components.

Table 23: Asking Right Question and Answering for course scheduling

Questions	Answers
How do daily hours effect course scheduling?	Course scheduling time slots is limited based on available time slots of days.
What is the contribution of university's classrooms in course scheduling model?	Number of university classroom is one of constraints in course scheduling model.
What is the contribution of university's regulation in course scheduling model?	University's regulations must be considered during course scheduling.
How do instructors effect the course scheduling ?	Instructors' preferences must be considered in course scheduling. Instructure performance also is important in course scheduling.
What is the contribution of students in course scheduling?	Students' preferences must be considered in course scheduling. Students' performance also is important in course scheduling.

Based on the aforementioned analysis, we realized that there are different criteria, which must be considered for course scheduling. Limited time slots during a day, limited classrooms of universities and instructors, students and administration preferences are different criteria for scheduling courses of an institute. In order to analysis impact of courses schedules on students' performance, we consider students as the main effective environment for course scheduling and analyze their relations and impacts on each other's.

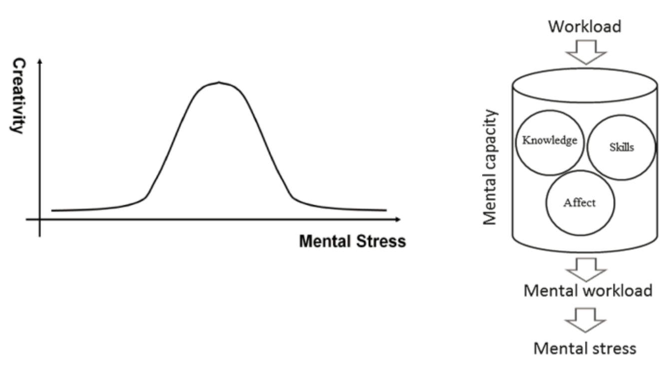
4.1. Course Scheduling and Academic Success

The course scheduling problem at higher education institutions deals with the assignment of courses in predetermined timeslots and classrooms based on the availability of faculty members and classrooms. The quality of course scheduling directly impacts the degree completion times. Furthermore, course scheduling is closely linked to the quality of the learning environment, through considering different criteria such as walking distances between consecutive courses, and break times for students and faculty members. The traditional course timetabling methods aim to ensure a feasible set of options for students to complete their studies within a given timeline by considering the constraints such as optimal classroom usage, course instructor preferences, and walking distances between classrooms.

In the present research work, we bring a new dimension to the course scheduling problem, which is the impact of mental stress on learning performance. We hypothesize that the consideration of that impact would lead to a superior learning environment. Through systematically blending the cognitive science and the operations research, a new course timetabling methodology is introduced.

Learning is described as a multi-stage process in the literature: i) unconscious incompetence, when an individual does not know and does not recognize; ii) conscious incompetence, when awareness of the lack of skills is developed; iii) learning stages, when skills are developed and applied (Cannon, Feinstein, and Friesen 2014). Environmental factors influence the learning performance, and the effectiveness of the learning environment depends on several factors. Al-Fraihat et al. (2017)categorize the factors impacting learning into 10 groups: planning, readiness, management, support, pedagogy, technology, faculty, institution, evaluation, and ethics. Sastry et al. (2016) studied the effectiveness of different teaching and learning techniques and concluded that teaching techniques are important in learning success. In order to further understand the impact of teaching techniques on learning quality, they surveyed 200 students to compare 17 different teaching techniques. Valsiner (1997) studied the impact of intellectual readiness, which is a function of knowledge, beliefs and interaction with the environment. Later, Geiger utilized Valsiner's zone theory to analyze how positive encouragement in class impacts the quality of learning (Geiger, Anderson, and Hurrell 2017). Anggrainingsih et al. (2018) further considered instructors' perspectives (financial policy, regulatory policy, course quality, relevant content, and technical support) and students' point of views (quality of course, relevance of content, completeness of content, attitudes toward peers, and flexibility in taking the course) as types of influential factors impacting learning quality.

Historically, the cognitive science literature has studied the impact of mental stress on learning performance. Wilke et al. (1985) showed the existence of a relationship between mental stress and learning performance. Their studies indicated that when individuals are subject to either too low or too high mental stress, their creativity will be significantly reduced. They further concluded that there exists an inverse U-shape relationship between mental stress and creativity. Later, Nguyen and Zeng (2012, 2016) formulated mental stress as a function of workload and mental capacity, and they defined mental capacity as a function of knowledge, skill, and affect (see Fig. 26 for illustration). The relationship between mental stress and creativity is provided in Figure 31(a); and an illustration of how mental stress is formed is provided in Figure 31(b).



(a) Mental Stress vs. Creativity

(b) Mental stress as a function of workload and mental capacity

Figure 31: creativity and mental stress relationship and mental capacity components (Nguyen and Zeng 2012).

It is known from cognitive science that a person's cognitive performance changes significantly during the day (Blatter and Cajochen 2007). Randler and Frech (2006) showed that morningness and eveningness influence school performance. Kleitman (1993) studied the relationship between the speed and the accuracy of cognitive performance and the time of day when a task was being completed. He studied subjects performing given tasks to understand if their performances change depending on the time of the day. As illustrated in Figure 32, Kleitman's work concluded that the cognitive performances of individuals change significantly during the day and follow a common pattern for the majority of the population. This study demonstrates that individuals perform best in the early afternoon and poorest during early mornings, late evening and night hours. Kleitman later explained that the variation in cognitive performance is due to variation in human body-temperature during a day (Kleitman, Titelbaum, and Feiveson 1938). Kelitman's findings are widely accepted in cognitive science and are frequently used in human performance studies (Randler and Frech 2006; Blatter and Cajochen 2007; N. Goel et al. 2013).

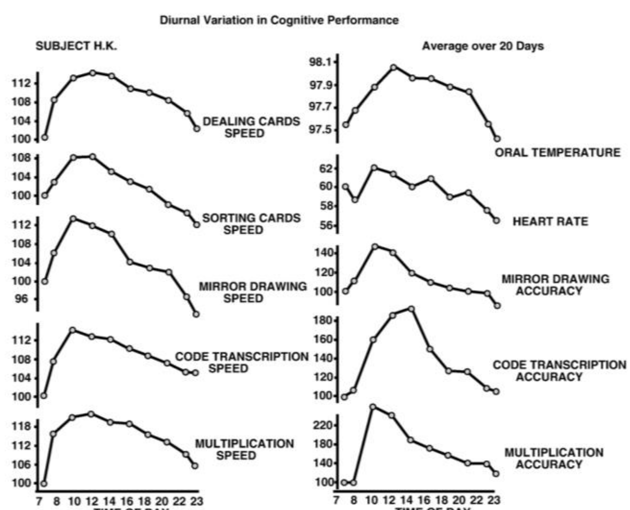


Figure 32: Effect of time of day in cognitive performance (Kleitman, 1933).

As discussed above, the learning performance varies depending on several factors. While several research results have been reported in the literature concerning factors that affect learning performance (Tatarinceva et al. 2018; Mohd et al. 2017), to the best of our knowledge, no academic study has considered timetabling as an influential factor for learning performance.

Degrees offered by universities consist of various courses with varying difficulty levels, which determine the required mental (cognitive) efforts to study those courses. It is suggested by Kelitman (1938), Randler and Frech (2006) , and Blatter and Cajochen (2007) that the cognitive capacity of individuals changes during the day according to Circadian Rhythm (see Fig. 2 for illustration). Furthermore, Nguyen and Zeng (2012) showed that people produce their best performances when they are subject to moderate stress, which can be achieved when the mental capacity and required workload are at similar levels (Fig. 26). Considering that Circadian Rhythm is a biological phenomenon and may not be controlled easily without medical intervention, the workload of courses should be matched with students' mental capacities to sustain the desired stress level that is optimum for learning performance. Accordingly, this research introduces a course scheduling method with an objective to minimize the difference between course workload and Circadian Rhythm, which is a measure of mental capacity in the present study.

4.2. Literatures review in course scheduling

Course scheduling and timetabling are treated as optimization problems, with an objective to optimize the usage of available facilities and to ensure the equitable consideration of students' and course instructors' expectations (Natashia Boland et al. 2008). A brief summary is provided below for the literature closely related to the proposed course timetabling problem.

Li and Li (2015) considered course characteristics (e.g., logical, experimental, analytical, etc.) as the foremost important factor in a course scheduling problem. Moreover, course duration (shorter duration has higher priority) and classroom sizes (larger class has higher priority) are incorporated in their course timetabling model as the secondary level influential factors. Ismayilova et al. (2007) proposed a timetabling formulation that optimizes overall preferences of both administration and course instructors. In their study, desired working conditions of course instructors are evaluated by utilizing the Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP), so that course instructors' preferences are fully incorporated in the decision making process. Several other researchers have also considered course instructor preferences in the modeling of course timetabling problems (Shiau 2011; Hakim et al. 2016; N. Boland et al. 2008; Gunawan, Ng, and Poh 2007) . Morrow (2017), on the other hand, analyzed the course timetabling problem from students' point of view with an objective to minimize the graduation time and the incurred costs.

The course timetabling problem has also been considered as a computational complex operations research problem (Pongcharoen et al. 2008). As the problem size increases (number of courses, classrooms, students and course instructors), converging to an optimum solution in linear time becomes highly unlikely. Consequently, a number of solution strategies have been proposed for solving timetabling problems in the literature. Yazdani et al.(2017) proposed three meta-heuristics (artificial immune, genetic algorithm, and simulated annealing algorithm) to solve a course timetabling problem. Their objective is to maximize instructor preferences while minimizing the number of classrooms used. Saptarini et al. (2017) and Aycan and Ayav (2009) utilized genetic and simulated annealing algorithms, respectively. Shiau (Shiau 2011) also introduced a hybrid particle swarm optimization method to solve the course timetabling problem.

Boland et al. (2008) proposed a blocking method where classes are partitioned according to their relevance so that the course timetabling problem can be solved in linear time.

As discussed in the aforementioned literature review, a large body of proposed mathematical models for course timetabling aims at addressing the expectations of administration and course instructors. Only a handful of studies are found to be studying course scheduling from the student point of view (Morrow, Hurson, and Sarvestani 2017). On the other hand, the cognitive science literature on learning quality considers student needs more closely in their models ((V. L. N. Sastry et al. 2017; Geiger, Anderson, and Hurrell 2017; Anggrainingsih, Umam, and Setiadi 2018). Hence, the objective of this research is to introduce the findings concerning learning quality from cognitive science into the traditional course timetabling problem. The ultimate goal of this timetabling model is to design a superior learning environment for students. In order to achieve this goal, the relationship between learning environment and learning quality is firstly established. Next, students' mental stresses are described as a function of their mental capacities and the course workload demands. Moreover, the controllable factors to regulate mental stresses are identified. Finally, a new course scheduling method based on learning capabilities is introduced. A mathematical model is formulated to produce a timetable for a set of scheduled courses with an objective to stimulate learning by keeping students' mental stresses at an optimum level.

4.3. Impact of learning environment on learning quality: Methodology and formulation

The course timetabling method discussed in this research requires a good understanding of the notion of course workload demands (difficulty levels of courses) and cognitive capacity of students. In order to incorporate these two attributes into a course timetabling formulation, the quantifiable measures that represent them must be defined. In the neuroscience literature, cognitive capacity is well defined as a function of a person's reaction speed and the accuracy (Kleitman, Titelbaum, and Feiveson 1938; Randler and Frech 2006; Blatter and Cajochen 2007) The literature further suggests that a person's cognitive capacity varies significantly during a 24-hour cycle which is known as Circadian Rhythm (Kleitman, Titelbaum, and Feiveson 1938). As seen in Figure 2, for a person performing various tasks, his/her performance during a day can be measured accurately. On the other hand, we hypothesize that the average GPA of a course is a good quantitative measure of the course workload demands.

As discussed earlier, mental stress (σ) is a function of required Workload (W) to perform a task and a person's cognitive capacity (C) (Nguyen and Zeng 2012, 2016). Hence we depict mental stress as:

$$\sigma = f(W, C) \tag{9}$$

Mental capacity, on the other hand, is defined as a function of Knowledge (K), Skill (S) and the environmental Affect (A). Hence:

$$C = g(K, S, A) \tag{10}$$

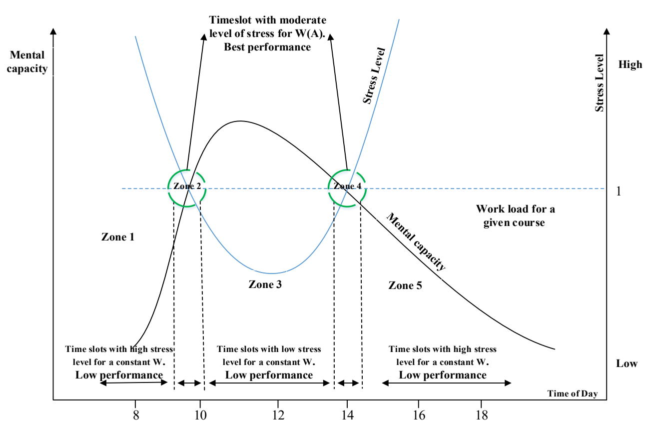
Consequently, we can measure the mental stress as:

$$\sigma = \frac{W}{C} = \frac{W}{(K + S) * A} \tag{11}$$

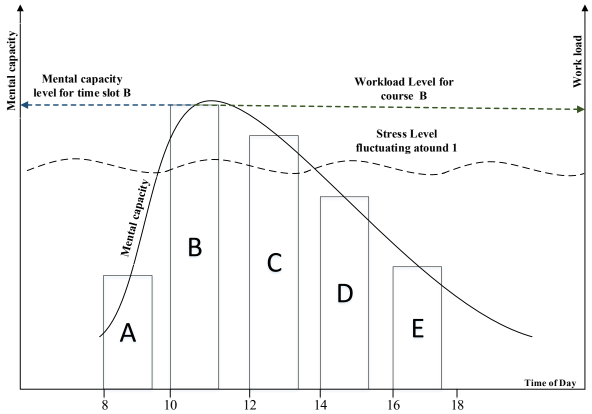
It must be noted that Eq. (28) is a qualitative representation of the causal relationships between mental stress and workload, knowledge, skill, and affect. From the literature, we further know that the quality of work (performance) (P) and mental stress has a U-shaped relationship. When σ is too low or too high, P tends to be lower (Wilke, Gmelch, and J.P. 1985). The literature suggests that people require a moderate level of stress in order to perform at their best (Nguyen and Zeng 2016).

Based on the aforementioned discussions, it can be concluded that academic institutions have the potential to stimulate students' learning performances by optimizing students' mental stresses through an optimal course scheduling. Factors impacting stresses are the course difficulty level (W) and mental capacity (C). The difficulty level of a course (W) is inherently coupled with the materials covered in the course and may not be easily modified. Hence, as part of this study, we assume that W is constant for a given course. Cognitive capacity, on the other hand, depends on three different factors: K, S and A. Students' competency at K and S are directly linked to the student's academic background. In this study we assume that institutions have already established a good curriculum map to ensure that their students develop the necessary knowledge and skills. The affect (A) varies depending on the environment. Therefore, through controlling the environmental factors, there is a potential to maximize the cognitive capacity of students and consequently their performance.

Let us now assume that A is defined as environmental factors impacting the learning performance. In most cases, environmental factors—such as the location of the campus, traffic conditions, pollution, and age of the infrastructure—may not be easily controlled by the university authorities. The objective of the decision makers should be to provide the best learning conditions by adjusting the controllable factors. In the context of the overall course scheduling problem, the controllable factor which is part of the environment (A) is the timeslots when courses are offered. Therefore, the objective of course timetabling should be to identify timeslots for course offerings based on their expected workloads (course difficulty levels, in our case) and the students' cognitive capacity, in such a way that the student's stress level is sustained at an optimal level for learning. From the literature, we know that Circadian Rhythm provides a good benchmark for the mental capacity. Hence, we hypothesize that the Circadian Rhythm is a good estimator for A. Therefore, based on the work of Nguyen and Zeng (2012), timetabling courses according to their difficulty levels (workload demands) in coordination with the Circadian Rhythm (less demanding courses are scheduled when mental capacity is low and high demanding courses are scheduled when mental capacity is high) has the potential to deliver a more favorable learning condition. Figure 28 illustrates how the students' stress level changes due to Circadian Rhythm for a given course. Since the workload of a given course (W) is constant regardless of the time of the day when it is offered, stress level, which impacts learning quality, changes significantly due to Circadian Rhythm. In Figure 33(a), the best timeslots to schedule this course would be Zones 2 and 4 where the moderate stress levels are observed. In Zone 28, the stress level is too low to stimulate students' attention. In Zones 1 and 5, students' stress levels are too high to cope with the course demands. Based on this analysis, we propose that academic institutions should develop course scheduling strategies to keep students' stress at an optimal level for learning. As seen in Figure 33(b), such an objective can be obtained by assigning less demanding courses in timeslots when cognitive performance is low, and more difficult courses in timeslots when cognitive performance is high.



(a): Different timeslots stress level for a constant workload



(b): sustaining a constant stress level by course scheduling (W(B)> W(A), W(B)> W(C) and W(C)> W(D))

Figure 33: Stress level variation based on Circadian Rhythm and constant workload

4.4. Hypotheses and assumptions

In order to achieve our objectives in this study, we introduced the following two hypotheses.

Hypothesis 1:

H0: Student stress level can be controlled using Circadian Rhythm in course timetabling.

H1: Student stress level cannot be controlled using Circadian Rhythm in course timetabling.

Hypothesis 2:

H0: Average course GPA is a good measure of the course difficulty level.

H1: Average course GPA is not a good measure of the course difficulty level.

There is an abundance of literature available related to the relationship between time of day and learning performance. A large body of the relevant literature finds a similar pattern called circadian rhythm where learning capacity is higher during late morning and early afternoon (Kleitman, Titelbaum, and Feiveson 1938; Blatter and Cajochen 2007). Based on the current literature, we conclude that Hypotheses 1 is valid.

In order to validate the accuracy of Hypothesis 2, we propose an Analytic Hierarchy Process (AHP)-based ranking methodology for measuring a course difficulty level. We developed a two-phase approach. First, expert feedback is consolidated to rank courses according to their difficulty levels, following the AHP as described in Akgunduz et al.(2002). Next, the correlation between AHP rankings (course difficulty levels) and class averages (average GPAs) are calculated using regression analysis to test the validity of Hypothesis 2. In order to perform the AHP analysis, the following assumptions were considered:

- Assumption 1: Instructors can compare courses on the basis of their difficulty levels.
- Assumption 2: Based on the findings of Engineers Canada (CEAB 2015), knowledge, problem analysis and design are selected as the most important criteria contributing to perceived difficulty levels

4.4.1. AHP Based Course Difficulty Ranking based on Experts Opinions

Since 1977, AHP has been applied successfully as a multi-criteria decision making tool to problems from healthcare to finance (Thomas L. Saaty 1977). The objective of the AHP is to rank different alternatives based on a number of criteria. Alternatives are compared against each other in pairwise groups. Based on the importance levels of criteria, the collected data are consolidated through AHP mathematics so that an unbiased ranking of alternatives can be obtained. AHP is an effective alternative comparison method particularly when the qualitative values are the only options for describing the criteria. Furthermore, AHP's capability for comparing a large number of alternatives with respect to a large number of criteria makes it a popular choice in decision science (Thomas L. Saaty 1977; Akgunduz et al. 2002; Chen et al. 2015).

Engineers are generally expected to excel in several technical and non-technical attributes. For example, 12 attributes are considered to be mandatory for an undergraduate engineering curriculum in Canada (CEAB 2015), in which students must successfully complete a set of prerequisite courses where the necessary background knowledge is taught and critical skills are developed. It was found that students' GPAs for a course are closely related to the three attributes targeted by the course – knowledge base for engineering, problem analysis, and design - and. When a course includes all of the three attributes, the course GPA tends to be lower (Table 24).

Table 24: Impact of Different Attributes on Course GPAs

Course	**KB**	**PA**	**D**	**Normalized averages GPAs from past 3 years**
ENGR 243	Intermediate	Intermediate	Intordoctory	0.83
MECH 215	Intordoctory	Intordoctory	Intordoctory	0.88
ENGR 244	Intermediate	Intermediate	Intordoctory	0.82
ENGR 233	Intordoctory	Intermediate	None	0.94
ENGR 391	Advanced	None	None	0.95
ENGR 371	Intermediate	None	None	1

A survey was developed to interview course instructors for verifying the observations made in Table 1 with the application of the traditional 5-level AHP ranking scheme (Aurup and Akgunduz 2012; Chen et al. 2015; Thomas L. Saaty 1977; T.L. Saaty 1980). A total of five full-time faculty members with at least 10 years or more teaching experience were invited to participate in the AHP study. The objective of the AHP study was to compare courses against each other so they could be ranked according to their difficulty levels. The following three-step approach was implemented:

i. Course instructors were asked to compare courses according to a given set of criteria in terms of their relevance to course difficulty level.
ii. Course instructors were asked to perform a series of pairwise comparisons between courses with respect to the first, second and third criterion independently.

iii. Responses from all faculty members and for all three criteria were consolidated using the AHP method, and the course difficulty levels were obtained in terms of AHP weight vectors.

Following the well-documented AHP based multi-level and multi-criteria evaluation technique Saaty (1980), the six-step approach below was adopted to evaluate the collected data from course instructors. The objective of the AHP analysis is to rank courses according to their workload requirements, which is a normalized measure of course workload requirements.

Step 1: Analyze each criterion evaluation matrix, similar to the one provided in Table 25, to obtain the relative weight of a criterion according to a single course instructor's opinion. This process generates a weight vector for each faculty member as:

$w^f = [w_1^f \; w_2^f \; \dots \; w_m^f]$, where f is the index of each faculty member and m is the number of criteria used in AHP.

Table 25: Comparison Matrix of Criteria (Which criteria has more impact on the difficulty level of a course?)

	Knowledge (K)	**Problem (P)**	**Design (D)**
Knowledge (K)	1	1	3
Problem (P)	1	1	3
Design (D)	1/3	1/3	1

Step 2: Consolidate the weights obtained from individual faculty members. Given that faculty members are equally qualified to evaluate a given set of criteria, the weight for each criterion can be consolidated by the simple average.

$$w_c = \sum_{f=1}^{F} w_c^f / F \qquad \forall \; criterion \; c \in [1, m] \tag{12}$$

where F is the total number of course instructors. Consequently, a weight vector (W) for the given set of criteria is obtained as:

$$W = [w_1 \; w_2 \; \dots \; w_m]$$

Step 3: Analyze each AHP matrix, similar to the one shown in Table 26, to obtain the relative weights (difficulty levels) of alternatives (courses). This process generates one set of weights (S_c^f) for a given criterion (c) for each faculty member as follows

$$S_c^f = \left[s_{1,c}^f \ \ s_{2,c}^f \ \ \dots \ \ s_{n,c}^f\right]^T$$

where n is the number of alternatives.

Table 26: Comparison Matrix of Courses with Respect to different criteria

(a) Knowledgebase in Engineering

	ENGR 243: Dynamics	**ENGR 242**: Statics	**MECH 321**: Properties & Failure of Material	**MECH 221**: Materials Science	**ENGR 391**: Numerical Methods in Eng.	**ENGR 311**: Trans. Cal. & Partial Diff. Eq.	**ENGR 371**: Probability & Stats in Eng.
ENGR 243	1	1.5	3	2	2	1.5	1.5
ENGR 242	1/1.5	1	2	1.5	1.5	1	1
MECH 321	1/3	1/2	1	1/1.5	1/1.5	1/2	1/2
MECH 221	1/2	1/1.5	1.5	1	1	1/1.5	1/1.5
ENGR 391	1/2	1/1.5	1.5	1	1	1	1
ENGR 311	1/1.5	1	2	1.5	1	1	1
ENGR 371	1/1.5	1	2	1.5	1	1	1

(b) Problem analysis in Engineering

	ENGR 243: Dynamics	**ENGR 242**: Statics	**MECH 321**: Properties & Failure of Material	**MECH 221**: Materials Science	**ENGR 391**: Numerical Methods in Eng.	**ENGR 311**: Trans. Cal. & Partial Diff. Eq.	**ENGR 371**: Probabilit y & Stats in Eng.
ENGR 243	1	1.5	2	1.5	2	1.5	1.5
ENGR 242	1/1.5	1	1.5	1.5	1.5	1.5	1.5
MECH 321	1/2	1/2	1	1/1.5	1/1.5	1	1
MECH 221	1/1.5	1/1.5	1.5	1	1	1	1
ENGR 391	1/2	1/2	1.5	1	1	1	1
ENGR 311	1/1.5	1/1.5	1	1	1	1	1
ENGR 371	1./1.5	1/1.5	1	1	1	1	1

	ENGR 243: Dynamics	**ENGR 242**: Statics	**MECH 321**: Properties & Failure	**MECH 221**: Materials Science	**ENGR 391**: Numerical Methods	**ENGR 311**: Trans. Cal. &	**ENGR 371**: Probability & Stats in

			of Material		in Eng.	Partial Diff. Eq.	Eng.
ENGR 243	1	1	1/3	1/3	1/3	1	1
ENGR 242	1	1	1/3	1/3	1/3	1	1
MECH 321	3	3	1	2	3	3	3
MECH 221	3	3	0.5	1	2	2	2
ENGR 391	3	3	1/3	1/2	1	1	1
ENGR 311	1	1	1/3	1/2	1	1	1
ENGR 371	1	1	1/3	1/2	1	1	1

(c) Design in Engineering

Step 4: Given that all faculty members are equally qualified to evaluate course difficulty levels, the weight for each individual course can be consolidated by the simple average.

$$S_{ic} = \sum_{f=1}^{F} s_{i,c}^{f} / F \qquad \forall course\ i \in [1, n];\ \forall criterion\ c \in [1, m] \tag{13}$$

Consequently, a vector $S_c = \left[s_{1,c}\ \ s_{2,c}\ \ \ldots\ \ s_{n,c}\right]^T$, which is independent from course instructors, is obtained.

Step 5: Scoring matrix $S = [S_1\ \ S_2 \ldots S_m]$ is established, where again m is the number of criteria.

Step 6: The relative difficulty ranking (R) of courses, according to all criteria based on the feedback from all faculty members, is calculated using Equation (14)

$$\mathrm{R} = \mathrm{S}\times\mathrm{W} = \begin{bmatrix} s_{11} & \cdots & s_{1m} \\ \vdots & \ddots & \vdots \\ s_{n1} & \cdots & s_{nm} \end{bmatrix} \begin{Bmatrix} w_1 \\ \vdots \\ w_m \end{Bmatrix} \tag{14}$$

In the present case, after evaluating the selected three criteria and seven courses with five faculty members, the following relative ranking of courses is obtained based on their difficulty levels.

$$R = \begin{bmatrix} 0.14 & 0.31 & 0.19 \\ 0.13 & 0.20 & 0.14 \\ 0.2 & 0.08 & 0.21 \\ 0.24 & 0.09 & 0.16 \\ 0.06 & 0.09 & 0.18 \\ 0.16 & 0.10 & 0.06 \\ 0.07 & 0.13 & 0.06 \end{bmatrix} \begin{Bmatrix} 0.41 \\ 0.42 \\ 0.17 \end{Bmatrix} = \begin{Bmatrix} 0.21 \\ 0.16 \\ 0.15 \\ 0.16 \\ 0.09 \\ 0.12 \\ 0.08 \end{Bmatrix}$$

4.4.2. Correlations between AHP Results and Course GPAs

Hypothesis 2 suggests that GPAs are good measures of course difficulty levels. In this section, we compare the AHP results with course GPAs in order to establish statistical relevance. Accordingly, a regression analysis on AHP results and GPAs from the past three years is conducted. Given that the AHP ranking is associated with the course difficulty levels, there must be a statistically significant negative correlation between course GPAs and AHP rankings (course difficulty levels in our context) to validate Hypothesis 2.

The calculated correlation coefficient (r) between these two data-sets is found to be -0.63, which demonstrates a strong negative correlation between average GPAs and the course difficulty levels. It is widely accepted that for $r \geq 0.5$ or $r \leq -0.5$, there exists a statistically significant correlation between a given two datasets (Cowan 1998). The normalized difficulty levels and the normalized average of GPAs of the analyzed sample along with their correlation coefficient are presented in Table 27.

Table 27: Comparison table between AHP ranking weights and GPA

Courses	Normalized **AHP** Ranking weights for difficulty level	Normalized averages **GPAs** from past 3 years	Correlation Coefficient
(ENGR 243)	1	0.798203	**-0.63**
(ENGR 242)	0.80875	0.77175	
(MECH 321)	0.630591	1	
(MECH 221)	0.625755	0.850831	
(ENGR 391)	0.409357	0.918278	

(ENGR 311)	0.514135	0.983111
(ENGR 371)	0.332848	0.959431

Next, the Analysis of Variance (ANOVA) is performed to measure the level of variability between the two data sets (GPAs and AHP results) to determine if the difference is statistically significant. The following five-step approach is utilized:

i. Calculate sum of squared deviation from the mean (S_{xx}, S_{yy}) and sum of the cross products of deviations from the means (S_{xy})

ii. Calculate total sum of squares: $SS_T = S_{yy}$

iii. Calculate regression sum of squares: $SS_R = \frac{{S_{xy}}^2}{S_{xx}}$

iv. Calculate error sum of squares: $SS_E = SS_T - SS_R$

v. Calculate mean square regression and mean square error: $MS_R = SS_R,\ MS_E = \frac{SS_E}{n-2}$

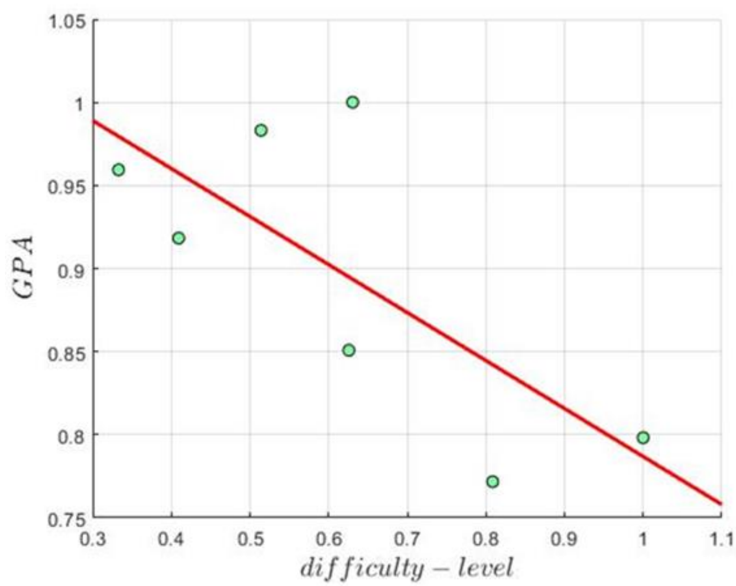
vi. Next, calculate the test statistics: $F_0 = \frac{MS_R}{MS_E}$

vii. Finally, compare the test statistics (F_0) against the theoretical F-distribution value for the given confidence level (α). For $F_0 > F_{2\alpha,f,v}$, it can be concluded that the evidence is insufficient to reject the NULL hypothesis.

The regression analysis, conducted on this study, where input data are the course difficulty levels and course average GPAs, results in the following sum of squared deviation from the mean (S_{xx}, S_{yy}) and sum of the cross products of deviations from means (S_{xy}): $S_{xx} = 0318$; S_{yy} = 0. 05; and S_{xy} = -0.092.

Consequently, the test statistics for ANOVA is calculated ($F_0 = 5.664$). For 95% confidence level ($1 - \alpha = 95\%$), the corresponding F-distribution value is $F_{\alpha,k,v} = F_{0.1,1,5} = 4.06$.

Considering that $F_0 > F_{0.05,1,5}$, it is concluded that the NULL hypothesis cannot be rejected. As a result, we claim that there exists a significant linear and negative relationship between average GPAs and course difficulty levels. Figure 34 presents the regression line and the test statistics for the samples.



a) Regression line

Source of variation	Sum of Square	Degree of freedom	Mean square	F_0
Regression	0.027	1	0.027	5.664
Error	0.023	5	0.005	
Total	0.05	6		

b) Test statistics

Figure 34: Regression analysis and variance analysis results

4.4.3. Why is GPA but not AHP to measure course difficulty?

According to the results of AHP, we are able to rank courses according to their difficulty levels. Given that an average engineering school offers several hundred different undergraduate courses in a given term, it may not be realistic to work with course instructors and students and conduct a survey to perform an AHP study. In order to find a practical solution to measure course difficulty levels, we conducted the aforementioned hypothesis test to explore if GPA is a credible measure of the course difficulty level. The regression analysis and ANOVA results support our hypothesis. Accordingly, we conclude that GPA is a reliable measure of course difficulty level (course workload in our context).

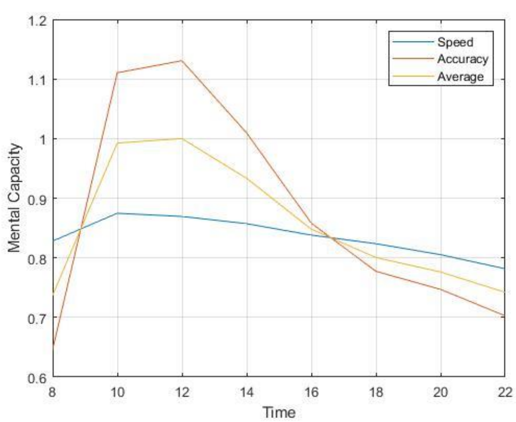
4.5. Mixed Integer Programming Model

A Mixed Integer Programming (MIP) model is formulated to solve the aforementioned course timetabling problem. In our case, we aim at designing a course schedule that maximizes the opportunities for improving the student learning performance. We hypothesized that by aligning the course schedule based on the Circadian Rhythm and course difficulty levels, a near constant student stress level can be achieved. As mentioned earlier, people learn/perform better when they are moderately stressed and the stress can be defined as a function of mental capacity and the workload. As depicted in Figure 28, the stress level is controlled by assigning individuals tasks according to their mental capacity. Since the mental capacity changes during a day according to the Circadian Rhythm, the only way to control stress level is by matching the course workload requirements with the student's mental capacity. This is achieved by assigning difficult courses to the time slot when the mental capacity is higher and less challenging courses when the mental capacity is lower. Accordingly, an objective function that minimizes the difference between the mental capacity and the course difficulty level is formulated. In other words, the objective is defined as the difference between standardized course difficulty levels (d_n) and the standardized mental capacity measures (C_l), which are non-dimensional quantities. The objective of the MIP models is to schedule N courses in M different classrooms during L timeslots available in a given day (D) where the total difference between course difficulty levels and mental capacity is minimized. The objective function is presented in Equation 17.

$$\min \sum_{n\in N} \sum_{m\in M} \sum_{d\in D} \sum_{l\in L} x_{nmdl} |C_l - d_n| \quad (17)$$

The decision variable $x_{nmdl} = 1$ if the course n is scheduled in the classroom m, at the l^{th} timeslot of the day d.

In order to compare the course difficulty levels and mental capacity objectively, both data are first normalized. Results from Kleitman (1938) for five different tasks are used to normalize the mental capacity (C_l). For the course difficulty level (d_n), the average GPAs from the past 3 years are utilized. We consider eight time slots based on Concordia University course scheduling practices, which starts at 8:45 AM, and finishes at 18:45 PM for most undergraduate courses. Figure 35 illustrates the mental capacity (C_l) of students at each timeslot during a day.



Times slots	Mental capacity (Speed)-Standardized	Mental capacity (Accuracy)- Standardized
8:45-10	0.853	0.869
10-11:15	0.874	1.109
11:15-12:30	0.869	1.119
12:30-13:45	0.862	1.099
13:45-15	0.854	1.033
15-16:15	0.840	0.935
16:15-17:30	0.836	0.844
17:30-18:45	0.861	0.799

Figure 35: Table and charts of mental capacity from Kletman (1933)

The optimization model includes three general constraints and two additional constraints specific to Concordia University. Equation (18) guarantees that each class is scheduled twice a week. Equation (19) ensures that there is no double booking in a classroom. Finally, Equation (20) ensures the assigning of a course at the same timeslot in two different days and in the same classroom.

$$\sum_{m\in M}\sum_{d\in D}\sum_{l\in L} x_{nmdl} = 2 \quad \forall \mathrm{n} \in \mathrm{N} \tag{18}$$

$$\sum_{n\in N} x_{nmdl} \le 1 \quad \forall m \in M;\ \forall d \in D;\ \forall l \in L \tag{19}$$

$$x_{nmdl} = \sum_{r\in D\backslash r\neq d} x_{nmrl} \qquad \forall n \in N;\ \forall m \in M;\ \forall d \in D;\ \forall l \in L \tag{20}$$

In addition to the constraints defined above, two additional constraints (21 and 22) are introduced to handle Concordia University's course scheduling practices: those courses offered twice a week must have a one-day gap in between two offerings (e.g., a course scheduled on Monday should be scheduled again on Wednesday).

$$x_{nmdl} = x_{nmd^-l} + x_{nmd^+l} \qquad \forall n \in N;\ \forall m \in M;\ \forall l \in L;\ \{d^-, d, d^+\} = \{1, 3, 5\} \tag{21}$$

$$x_{nmdl} = x_{nmd^+l} \qquad \forall n \in N;\ \forall m \in M;\ \forall l \in L;\ \{d, d^+\} = \{2, 4\} \tag{22}$$

It should be noted that the course timetabling model introduced above is the most basic formulation. The main focus of this research is to introduce the learning performance in the objective function. More complete models that include constraints such as availability of faculty members, student course sequences, classroom sizes, and travelling times between classrooms are available in the literature (Morrow, Hurson, and Sarvestani 2017; Shiau 2011; Hakim et al. 2016; Natashia Boland et al. 2008; Gunawan, Ng, and Poh 2007; Carter and Laporte 2006; Dimopoulou and Miliotis 2004). In this research , such details are intentionally omitted in order to provide a better coverage of the relationship between course scheduling and the learning environment.

4.6. Case Study

The corresponding mathematical model is solved using IBM ILOG CPLEX Optimization Studio 12.2, using Optimization Programming Language (OPL) on a personal computer with 64-bit operating system, 3.40 GHz Intel Core i7-2600 CPU and 16.0 GB RAM. CPLEX provides a number of alternative solution methodologies for the MILP models. We utilized the Branch and Cut (BC) algorithm to solve the sample cases. For defining the boundary of the problem, the following conditions are considered:

i. Courses can be scheduled from Monday to Friday.
ii. There are a total of eight timeslots per day for undergraduate courses to be scheduled.
iii. All courses require 1 hour and 15 minutes of class time, twice a week:
   a) Monday courses are offered again on Wednesdays at the same time, in the same classroom
   b) Tuesday courses are offered again on Thursday at the same time, in the same classroom
   c) Wednesday courses are offered again on Friday (if not offered on Monday) at the same time, in the same classroom.
iv. Classroom sizes are not considered as a constraint.

Since the university has more classrooms than what engineering programs need (classrooms are shared among all faculties), first the optimization problem is solved with an objective to schedule all courses with a minimum number of classrooms. It was identified that a minimum of five classrooms is needed to schedule 80 undergraduate courses. Given that each course requires two timeslots per week, a total of 160 teaching slots are needed. With the available eight timeslots per day, five classrooms provide a total of 200 teaching slots per week.

Next, the main model is solved to maximize the learning performance. In order to measure the improvement opportunities, the problem is solved with a different number of available classrooms (5, 10 and 15 classrooms). Finally, the results are compared with actual schedules from previous years (2013, 2014, 1015 and 2016) to demonstrate the improvement opportunities in the learning system. In Table 28, results for three different classroom capacities for each academic year are compared according to the objective function and the computation times. The number of classes scheduled in each academic year varies between 71 and 80. As expected, when the number of available classrooms is increased, the objective function, which measures the difference between Circadian Rhythm (mental capacity) and course difficulty level, decreases. This means that students' learning experience would be improved.

Table 28: Comparing current schedules with proposed schedules

Academic Years	**Objective Function**			**Computation Time (in seconds)**			**Number of Courses**
	Plan A (5 classrooms)	**Plan B (10 classrooms)**	**Plan C (15 classrooms)**	**Plan A**	**Plan B**	**Plan C**	
2013	18.139	13.75	12.067	0.72	1.23	1.57	80
2014	13.399	9.643	8.476	0.76	1.19	1.48	74
2015	11.680	8.305	7.598	0.68	1.06	1.48	71
2016	12.21	8.332	7.339	095	1.24	1.65	75

In order to demonstrate the differences between the mental capacity and difficulty levels for all courses before (using the current schedule-dash lines) and after applying the proposed timetabling method (solid lines), we plot the objective function for all courses (new schedule is generated with 15 classrooms). All four sub-figures in Figure 36 clearly demonstrate the improvement opportunities in the current timetabling methods.

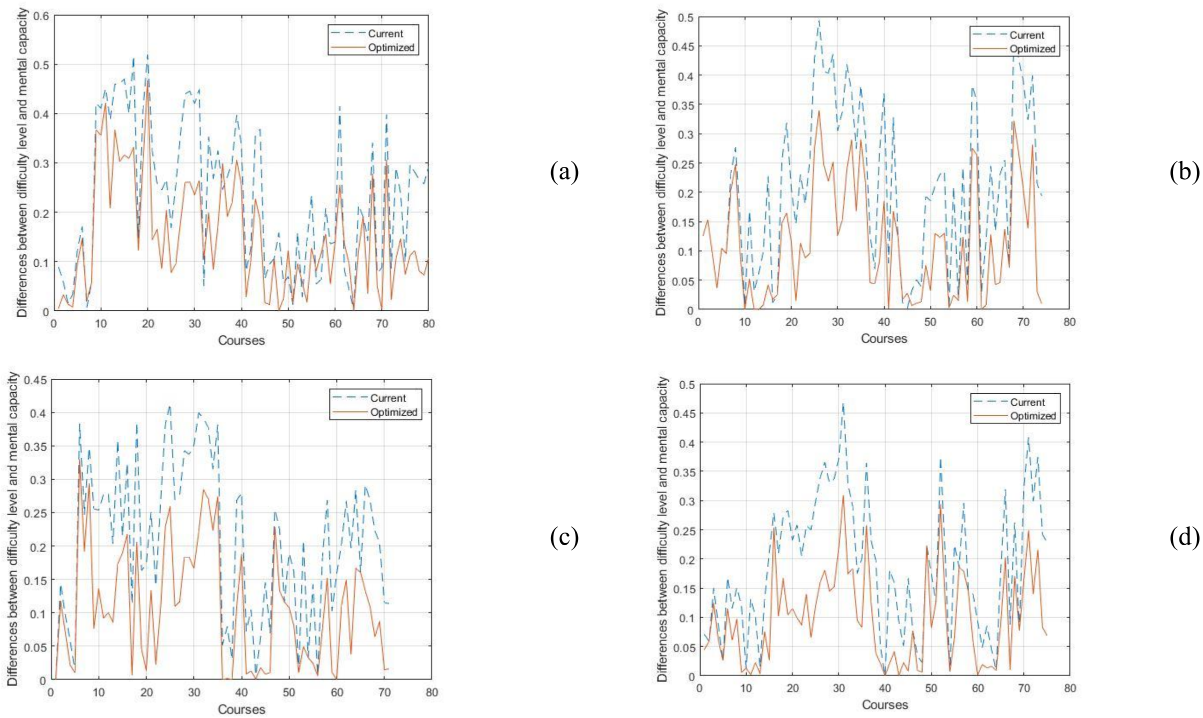


Figure 36: Differences between Mental Capacity and Difficulty Level for all courses though at 2013 (a), 2014 (b), 2015 (c) and 2016 (d).

This research introduced a novel course timetabling model that has potentials to improve student learning experience in higher education institutions. Previously, several different course timetabling models have been proposed, with consideration of different criteria such as faculty member preferences, administration objectives, course sequences for the degree, and financial expectations. To the best of our knowledge, the impact of course scheduling on student learning performance has not been studied previously. In this part of our research, we formulated student success as a function of mental stress. Furthermore, we demonstrated that, through course scheduling, a student's mental stress can be maintained at a level which is more desirable to stimulate learning performance. After defining mental stress as a function of "required workload to perform a task" and "available mental capacity," we provided an AHP-based technique to define the "course workload" in terms of average course GPA. Given that a student's mental capacity changes according to their circadian rhythm during a day, an integer programming model is formulated for timetabling courses in such a way that students are stimulated optimally due to the maintenance of their optimum level of mental stresses. The proposed integer programming model has been applied for timetabling of engineering courses at Concordia University in Montreal. Results indicate that there are significant opportunities to improve current course scheduling practices to provide better learning environments for students.

5. Conclusion and future work

In this research, different applications of EBD methodologies is presented. It is showed that EBD is capable of performing product evolution analysis, it can be utilized for designing complex products and also help to consider more aspects of students during scheduling courses. Product evolution analysis needs a design methodology, which is capable of defining the driving forces, identifying necessary resources and deriving potential direction for future of product. We demonstrated through a case-study of braking system evolution that EBD can perform all three aforementioned tasks through environment analysis, conflict identification and solution generation. Finally, we predicted the future of braking systems based on their EBD analysis results. We also presented a conceptual configuration for the future of braking, but a detailed design and analysis is also needed which we postpone for the future works.

Afterward, we considered aerospace products and specifically civil aircrafts as the most well-known complex systems. We recognized their design and management methodologies as the main reasons for many problems during their products' development. In order to propose a novel design and management methodology for developing complex systems such as civil aircrafts, we reviewed current design methodologies of aerospace industries. Consequently, we proposed a novel methodology, which is a combination of EBD with SE, QFD, AHP, Lean, Kanban and Agile models, AD, trade studies and decision support systems. In order to verify efficiency and effectiveness of the proposed methodology, we need to utilize it during a real project. Considering huge amount of time, budget and efforts, which are needed for performing a complex product designing project, we left the verification of design methodology for future.

Finally, we propose a novel course scheduling model by considering students as the main environment of courses' schedule. We utilized a combination of stress-performance model and Circadian Rhythms for increasing students' performance and consequently their GPA during different courses. We also tested our mathematical model by rescheduling Concordia University's courses. Instructors and administrations' preferences are not considered in our course scheduling model and our model is capable of scheduling Concordia University's courses with a constant duration. Hence, in the next steps of this part of research, we need to add other constraints to our model, which help to schedule courses more practically.

We revealed different capabilities of EBD in this research and we showed that product's environments analysis leads to product specifications. We utilized EBD for planning of each project and for their detailed analysis. Further applications of EBD in design and product development can be considered in future works.

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