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School of Business and Management

Department of Industrial Engineering and Management

Global Management of Innovation and Technology

MASTER'S THESIS

TOWARDS RADICAL INNOVATION: MATHEMATICAL MODELLING AS A CREATIVITY TECHNIQUE IN CHEMICAL MIXING PROCESS

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ABSTRACT
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Innovative solutions cause a boom in a company's sales, and consequently a surge in its profits. These solutions stem from creative ideas that bring novelty to the firm's activities. Recently, there has been a growing attention to the concepts of systematic creativity and creativity management in academia and industry. Mathematical modelling is a well-known tool for optimization purposes in many fields, but not as a technique for New Product Development (NPD) or new services and processes. The focus of this study is on the role of mathematical modelling in making breakthroughs in chemical mixing process. Mathematical models and simulations used for finding new ideas in chemical mixing process. The selected idea was proved to be a technologically and economically feasible alternative for replacement in chemical mixing process. It was found out that there were similarities between the mathematical modelling approach for creativity process in this study and Helmholtz-Poincare-Getzels (HPG), a famous creativity process model. The former was more dynamic, less likely to result in accidental creative ideas and more iterative. Thanks to the possibility of simulating the models, mathematical modelling could give visual illustrations of the model and consequently increase the likeliness of finding creative ideas. The ability to simplify the problem by mathematical models gave a higher chance and flexibility to find creative solutions including the applications for other tasks or industries. To exploit the most out of mathematical modelling in Research and Development departments towards radical innovation, managers should require higher level of math's and simulation skills from the current and prospective employees. Innovation-wise, Finland is a stunning country and a suitable environment at both micro and macro levels. In order to increase the popularity of systematic creativity (mathematical modelling technique in particular) in Finland, it is suggested that more budget should be assigned to universities for including creativity-related courses such as mathematical modelling and TRIZ in their curricular to increase the productivity in Finnish society. Joint creativity seminars for organizations proved to be a good strategy to change the direction of the employees' insight to problem solving. It is crucial to increase the motivation of management and employees as it pertains to creativity workshops.

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ABBREVIATIONS

AD Axiomatic Design

CEO Chief Executive Officer

DFSS Design for Six Sigma

DP Design Parameters

EU European Union

FOS Function-Oriented Search

FR Functional Requirements

GDP Gross Domestic Product

GM General Motors

HPG Helmholtz-Poincare-Getzels (creativity process model)

HR Human Resources

HVAC Heating, Ventilation and Cooling

IFR Ideal Final Result

JIT Just-In-Time

MA Morphological Analysis

NPD New Product Development

OECD Organization for Economic Co-operation and Development

QFD Quality Function Development

R&D Research and Development

RIC (National) Research and Innovation Council (in Finland)

SCAMPER Substitute, Combine, Adapt, Modify, Purpose, Eliminate, and Reverse (seven thinking skills for brainstorming)

SIL German acronym for Systematic Integration of Problem Elements

SITRA Finnish Innovation Fund

TEKES the Finnish Technology and Innovation Funding Agency

TQM Total Quality Management

TRIZ Teorija Reshenija Izobretatelskikh Zadach (the Russian acronym for the Theory of Inventive Problem Solving)

VC Value Creation

VINNOVA Verket för innovationssystem (the Swedish Research and Funding Agency)

1. INTRODUCTION

First, a brief background to the identified problems is introduced in the first sub-chapter. The chapter is then followed by describing the research gap, determining the objectives of the research and formulating the research questions. The third sub-chapter is devoted to the methodology used for conducting this research and finally, the paper structure is described in the last sub-chapter.

1.1 Research background

Companies and markets became so dynamic that makes it difficult for one to predict the future of the industries, technologies, products, services and business models. The competition in the markets are so tight, stressful and complicated that lead all firms to continuously think about new solutions and strategies to survive. When it comes to large firms and industries, this fact is highlighted and may result in significant profits or losses. For instance, having been the biggest car producer in the world, General Motors (GM) was suffering from the fall of their sales because of their Japanese competitors such as Toyota despite the fact that GM manufactured cars with the least expenses in the US (Jain & Sanchez, 2008). There were many reasons behind the failure of GM in competition with Toyota at that time including cultural issues, quality, variety of products and their features and more. It is therefore, of a great importance for any firm to continuously consider the business, make improvements to their weaknesses and exploit the opportunities seen potential to make revolutions in their business and industries. The later describes *disruptive innovation* where companies push frontiers to new technologies and concepts. For example, back in 17^{th} century, the new idea of small plants for steel industry-so called “mini mills”- changed the business model, the production cost decreased dramatically which in turn caused a higher profit margin in the industry. Another example is the sudden change of the size of the computer disks over the period of thirty years, where the 14-inch computer disks replaced by 3.5-inch floppy discs in three cycles. The very famous example for disruptive innovation in recent times is 3D printing technology that enables companies to easily prototype the physical objects of their interest after simulations (Vertakova, et al., 2016). These examples show that larger companies, especially those involved in high-tech such as automotive or chemical industries, should pay a special attention to their innovative activities to be able to sustain their leadership by continuous novelties. Because, the new product introduced to the market today can be perceived obsolete quite soon (Maidique & Zirger, 1984).

Chemistry and chemical industries have played the greatest role over the last centuries in producing innovative products and is known as the leading industry in innovation, since it provides other industries with the material needed for their activities (Kreimeyer, 2010). This has apparently affected the life of human beings with countless examples of plastics, fertilizers, dyes, medicine and more. Being the leader of innovation, firms in pharmaceutical and chemical industries introduce many new products in a short time that in turn changes the paradigm in many other industries. Innovation, however, in chemical industry is not limited to products only. It can cover the aspects of processes as well as services. It can be challenging to assign a context to an innovation in chemical industry, because, for example, a product such as a reactor for wastewater treatment plant can perform the sophisticated process of transforming wastewater to clean water in a plant and is perceived as a service. The study by Potiero & Camargo (2012) can be useful for more information on innovation topics in industrial process management.

Every successful innovation regardless of its impact in industries starts from generation of a new idea. Industrial leaders often concern about the lack of creativity in their employees and this concern is a big problem in a world where technology is progressing drastically (Ogot & Okudan, 2006a). One barrier to the enhancement of individuals' creativity level is the hierarchy in the organizations that does not allow them speak up their new ideas (König, et al., 2006). Every person can learn skills that makes her better at problem-solving and increase the potential of individuals in being more creative (Ogot & Okudan, 2006b). The initial idea behind any internal R&D department in organizations is contribution to the innovation process by the company itself. Thus, having believed that systematic creativity fosters the process of innovation and the fact that creativity can be boosted by learning specific skills and methods, organizations should spend more time and assign more budget to make improvements to their system. The innovation process in chemical industry usually starts by creativity phase in the processes, coming up with new products and introduction of the product to the market.

Creativity in chemical industries often consists of three differen stages of divergence (generation of new ideas regardless of their base and values), convergence (idea evaluation and selection) and creativity under constraint where the best ideas are selected by considering the financial, technical, technological, social and environmental limitations (Maidique & Zirger, 1984).

1.2 Research gap, objectives and questions

Mathematical modelling is perhaps one of the most powerful tools in science and technology which contributed to advancements in many different areas. There is an extensive literature about the application of mathematical modelling in technical science and humanities. Laland (1993) describes the application of mathematical modelling in human culture, psychology and genetics, and how innovative ideas can appear by using it. Minns (1994) emphasizes that by using mathematical modelling, an organization is able to predict the future of the environmental and economic policies by governments and making decision for R&D investors becomes easier. Mathematical modelling was proved to be a handy tool for designing new cost-effective drying technologies with less carbon emissions (Mujumdar & Zhonghua, 2008). There can be found many more examples where mathematical modelling were used as a tool to describe the dynamics of the systems and optimize them and, consequently, make improvements to products, services or processes. However, the literature lacks sufficient empirical research on the deliberate application of mathematical modelling as a creativity technique for making breakthroughs and radical innovation.

Mixing process is one of the most common processes in chemical industries. In a typical mixing process with mechanical agitation, there could be huge costs for energy supply, time restrictions, huge expenses and room for big tanks and many other problems. These problems make one think about new ideas to overcome the difficulties. Here, the aim is not to make improvements to the system by optimization of the tank volume or consuming less energy by different agitators. It is more desirable to find out the approaches that end up in radical innovation. For instance, it is captivating to find a solution by minor changes to the system, where the need for mechanical agitation tank for mixing purposes is eliminated completely while the function is performed.

The major objective of this study is to discover the role of using mathematical modelling as a systematic creativity technique in problem-solving for making innovative breakthroughs in chemical mixing process. Accordingly, the following research question is formulated for the study:

RQ1. How the application of mathematical modelling as a creativity technique can contribute to radical innovation in chemical mixing process?

1.3 Methodology

The research strategy was a holistic single case study on industrial mixing process, particularly based on the paper written by Yakovis & Chechurin (2017). The paper was analyzed deeply and the theoretical assumption on the effect of passive control over inflow without mixing equipment (which was done through their mathematical model) was tested and simulated. The research strategy since then changed to grounded theory in search for creative ideas throughout mathematical models. Two new ideas were generated at this stage including active control over inflow and simultaneous dosing and mixing process. Both ideas were then technically, technologically and economically investigated in more depth. Complementary qualitative analyses for confirmation of data and interpretations was required for further steps of analyses. For that purpose, three separate unstructured interviews were conducted with three experts in chemical industries, where findings were discussed at each stage from the chemical and technical point of view.

The exploratory nature of the RQ1 required quantitative analyses and simulations to realize the influence of mathematical modelling on creation of new ideas. However, qualitative methods such as unstructured interviews were combined with the quantitative analyses. Deploying multiple sources of data (triangulation) resulted in more credibility of the outcomes from this research.

For the quantitative part of the analyses, experiments through simulations were deployed to test the assumptions on mathematical models. One point to consider is that Simulink (simulation tool of MATLAB software) was used to analyze the system. There were other alternatives to check and simulate the behavior of the systems (i.e. LabView, VisiMix and so on). However, the main reasons to use Simulink for this part of the study were its accuracy of simulation, comprehensive tools for simulation and appropriateness for this study. Having completed the search and got to know to the basics of modelling by MATLAB and Simulink, the author was enabled to work on the problem of the case study

The reliability of the collected data throughout simulations was confirmed by several observations for each simulation where all data gathered were consistent with negligible deviations. The arithmetic average of findings were used for further data analysis. Since the independent variables were controlled and only one variable affected the dependent variables, the causal relationship between the variables, hence the validity of the data confirmed.

1.4. Research structure

The structure of the thesis after the introduction is as follows: The research starts by a comprehensive literature review in Chapter 2 over the main related concepts, which would be introduced in the theoretical framework and investigated in further details. The empirical part including the general required knowledge of industrial mixing process, problem recognition, ideation phase and a summary of the results and simulations are described in full details in Chapter 3. The Discussion part in Chapter 4 comprises the practical implications of the study, main characteristics of the mathematical modelling as a creativity technique and the possible strategies to popularize this approach in Finland. The research is concluded in Chapter 5 by presenting the contributions to academia, managerial implications of the study, research limitations and possible further research fields.

2. LITERATURE REVIEW

The theoretical framework covered by this study contains different areas of technology and innovation management. In fact, all the theories and concepts used for the literature review are integral parts of Innovation Management theory and Systems Engineering. The main focus of this study is the portion of the literature where these two meet and have common characteristics. This portion is called ‘Systematic Creativity’ where creativity techniques as a part of systems engineering process contribute to innovation, mainly at micro-level (firms and organizations). Accordingly, the literature review is divided into three subchapters including innovation management, systems engineering and systematic creativity. The Figure 2-1 demonstrates the theories used for the theoretical part of this study to give a better understanding of the focus area.

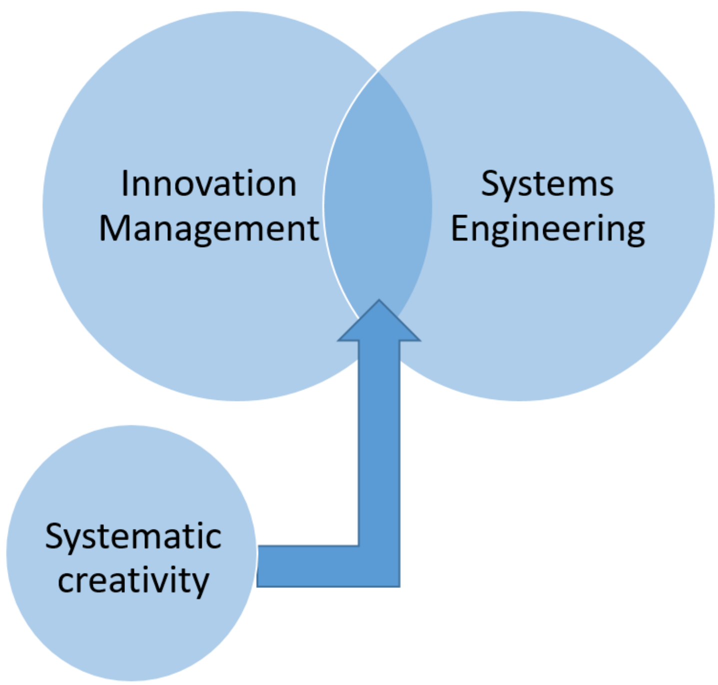

Figure 2-1: Theoretical Framework

2.1. Innovation Management

Innovation Management defined by Weis (2015) as a systematic management and control of innovation in an organization in the way to best benefit from ideation until a successful commercialization of a product or service. It consists of six stages including Ideation, Preliminary Analysis, Business Case, Product Development, Test and Validation, and Market Launch (Weis, 2015). However, this process is not as easy as it might seem, because many uncertainties are involved within the whole process and makes it quite complex and challenging (Akhilesh, 2014).

Even though the management of innovation in one company differs from another, there are certain mutual "*patterns"* that could be considered as success factors in innovation management. For organizations to be able to successfully manage innovation, it is vital to make their strategies towards innovation clear. They must know their direction and areas where they are willing to be innovative and pay a careful attention to their portfolio of innovation-related projects. The process of innovation should also be quite clear and systematic in all stages from conceptualization to retirement and must take all market aspects of the process into account. A precise and detailed management is required all over the projects. Finally yet importantly, the culture of innovation in firms play a significant role in their innovativeness. Not only employees should understand this culture, but management should also support innovation in their activities (Gaubinger, et al., 2015).

2.1.1. Innovation

The very first step to analyze innovation is to realize what it is and how different it is from creativity and invention. "*Novelty*" or "*newness"* is the most important property of an innovative product or process (Varis & Littunen, 2010; Gaubinger, et al., 2015). Innovation is different from creativity in that creativity refers to the stage where a new concept is ideated, but innovation is the successful implementation of the developed ideas in creativity phase (Patterson & Zibarras, 2017). There is also a distinction between an invention and innovation that if an invention is not successful in the market, it would stay an invention and by no means an innovation (Tidd & Bessant, 2009; Gaubinger, et al., 2015).

2.1.2. Innovation drivers

Another step of innovation analysis is to understand why it is crucial in today's world and every single organization should take it into consideration. The level of competition between organizations involved in any industry and their dynamicity is so high nowadays that makes the market full of stress and complexity (Gaubinger, et al., 2015) Regardless of their size and type of activities, organizations and firms could hardly exist without making continuous changes to their strategies over time. In large companies such as BMW, there is a special laboratory for innovation and many experts from different fields of science get together to contribute to innovative products (Gaubinger, et al., 2015). There could be different reasons behind the changes that make decision-making process more and more complicated. Undoubtedly, globalization is the most important and challenging driver of innovation. Despite bringing many new opportunities and access to new markets, it can have its own threats for domestic production because of possible cheaper price of final foreign products or services. Another important factor that makes innovation as an integral part of today's business is uncertainty (Akhilesh, 2014) and the main task of innovation management is discoloring the influence of uncertainty on business performance (Tidd & Bessant, 2009). Pressure from markets and thirst for new products lead firms to come up with new ideas and technologies (Kruger, 2008). Tidd and Bessant (2009) believe that "need" affects the process of innovation significantly, meaning that if an invention is not introduced to the market at the right time, can be unsuccessful. Continuous change of client requirements forces firms to think of new ways of making things happen by for instance cost reduction or product/process differentiation (Reijonen & Pinheiro-Croisel, 2017). In fact, many innovative ideas commercialize in the era of constraint and limitations. For instance, BASF activities related to innovation did not stop in the global crisis of 2008 (Kreimeyer, 2010). The history of BASF, shows that the company was innovative in the prior crisis eras such as invention of Kaurit glue in 1930s, magnetic tapes in 1934 and styrene synthesis in 1929. The Figure 2-2 depicts the drivers of innovation in today's business world.

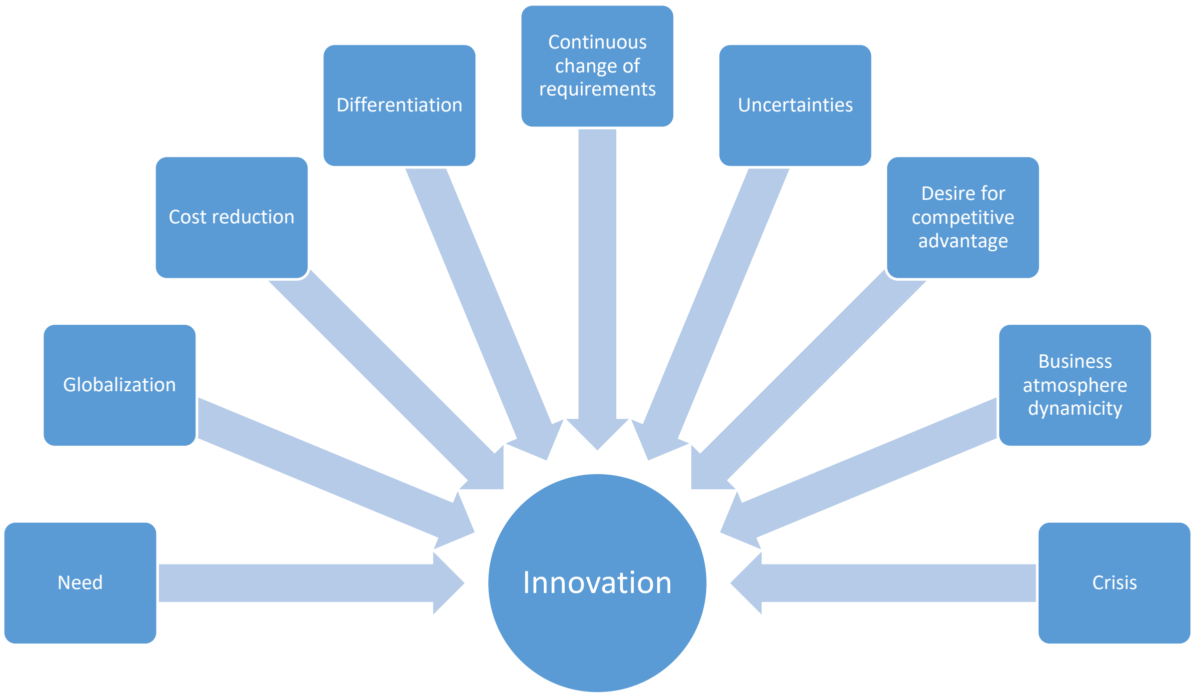

Figure 2-2: Innovation drivers

2.1.3 Innovation sources

One of the important facts about innovation to investigate is its sources and origins where they come from. Here, one should distinguish between the source of innovation and creativity. Tidd and Bessant (2009) classifies the source of innovation to accidents, system shocks, imitation, idea generalization, advertising, inspirations and so on whereas A.Schilling (2013) believes that the dimension for innovation is based on the interaction of the innovation stakeholders such as users, organization staff, R&D departments, universities, alliances, government and non-profit organizations. The author of the thesis argues that the former typology considers different situations where creativity occurs and not necessarily innovation. The source of innovation may significantly influence on an organization's strategy towards innovation.

2.1.4. Innovation typology

The dimensions, according to which innovation is classified could vary. There exist many different typologies for innovation in the literature. For instance, A.Schilling (2013) investigates innovations typology based on the following four dimensions. The Table 1 demonstrates her taxonomy for innovation concisely.

1. Whether the innovation is related to a product or to a process: It is essential to differentiate between the innovation in products and processes, because the strategies for each could direct one towards different ideas. Tidd and Bessant (2009) believe that the benefit of process innovation is almost four times more than product innovation.
2. The significance of the innovation (could be radical or incremental): Based on the degree of change made to a current product/process, the innovation could be considered as "*radical*" or "*incremental*". If the new product/process brings a new concept to markets (thinking out of the box), the innovation is considered as radical. But, if improvements are made to optimize the system performance, the innovation would be called incremental.
3. The influence on existing knowledge and products: An innovation could make a firm grow by cumulative knowledge saving, which then to be exploited for further development. Yet, it can be disruptive for other products/processes and causes other products to be eradicated from markets. The former is "*Competence-Enhancing*" while the second is called "*Competence-Destroying*".
4. The effect of innovation on the overall architecture of systems: An innovation could be perceived "*Architectural*" if it affects the design and architecture of the product/process reasonably. But, if the innovation only changes the design of a system component and does not have a significant influence on the architecture of the system, the innovation would be "*Component Innovation*".

Table 2-1: Innovation typology (source: A.Schilling, 2013)

	Dimension of Innovation	**Type 1**	**Type 2**
1	Being a product or a process	Product Innovation	Process Innovation
2	The significance of innovation	Radical Innovation	Incremental Innovation
3	The influence on existing products/processes with similar functions	Competence-Enhancing	Competence-Destroying
4	The influence of innovation on the overall architecture of the system	Architectural innovation	Component Innovation

2.2. Systems Engineering

In order to investigate systems engineering and its impacts on further developments of products and processes, one should consider the major definition, elements, concepts and taxonomy of systems. There are very different definitions for a 'system' in the existing literature. However, the most recent scholars of systems engineering (Fabrycky, (2014); Moser, (2014)) have common believes on the characteristics of a system. According to their studies, a system consists of interrelated components (objects) of different attributes (properties of the components). This relationship, however, should be a functional relationship that contributes to the system performance and function and not all objects with relationships could be defined as a system (Fabrycky, 2014). Each component itself can be considered as a subsystem (with the same definition of a system mentioned above) and more complex systems consist of many subsystems in a determined hierarchy (Fabrycky, 2014).

Moser (2014) cited several definitions for 'Systems Engineering' from the literature of the 19th and 20th centuries, whereas Fabrycky (2014) believes that there is no consistent definition for systems engineering in the literature. However, they all have common believes on the characteristics of systems engineering. Systems engineering is a *top-down multidisciplinary* approach of a system engineer or an organization in order to fulfill the requirements of customers and satisfy their needs (Fabrycky, 2014). Another important characteristic of systems engineering is that it is an *iterative process* over the entire lifecycle of a system (Eisner, 1998). A system engineer's tasks include but are not limited to translation of customer needs into engineering requirements, a full description of a set of operations to be done to fulfill technical requirements and their compatibility, future vision for maintenance and providing high safety of personnel and equipment (Fabrycky, 2014). Although there exist main principles of systems engineering, individual's approach to its implementation could vary. These differences may stem from various backgrounds of the people involved in and with the system, the nature of the system and the objectives to be achieved (Fabrycky, 2014). Needless to say is that these differences may change the strategies and the directions of the organizations completely. For instance, the decision whether radical changes or improvements to a system is essential or not may change the insight of the management to the market significantly.

The level of complexity in a system depends on the number of disciplines (functions) and the number of stakeholders of the system. Previous studies reviewed by Moser (2014) shows that there are different believes on the definition of 'System Thinking'. Having said that, nearly all the authors cited in Moser (2014) study of systems engineering are of the opinion that system thinking is the ability to see the whole picture of a system and recognizing the major elements and relationship in a system (Moser, 2014). These may provide a systems engineer to analyze a system and make improvements and required changes to the system more quickly and efficiently.

2.2.1. Systems classification

Fabrycky's (2014) classification of systems include different criteria to analyze a system. These criteria include the origin of systems (made by nature or human being), physicality of systems (physical or conceptual such as simulations), dynamicity of systems (static or dynamic) and the presence of interaction with the surrounding environment (open or close systems). The Table 1 represents the classification of systems by Fabrycky (2014).

Table 2-2: Systems classification (source: Fabrycky, 2014)

	Criterion of classification	**Type 1**	**Type 2**
1	Origin	Natural	Human-Made
2	Physicality	Physical	Conceptual
3	Dynamicity	Static	Dynamic
4	Interaction with environment	Open	Close

2.2.2. Systems Lifecycle

Considering a system and its characteristics, one may end up in that products can be seen as systems and come up with a lifecycle for them. In fact, in complex systems, the system functions are performed by the well-known products involved in the system (Fabrycky, 2014), such as major products used in HVAC (Heating, Ventilation and Cooling) systems. All products and systems have got their lifecycle and it is of paramount importance for a system engineer to take the system lifecycle into account. Fabrycky (2014) is of the opinion that systems lifecycle includes two phases of acquisition and utilization. In his description to the phases shown in the Figure 2-3, the former consists of conceptual (preliminary) design, detailed design and production, whereas the latter is broken down into usage systems (products), support and maintenance, the retirement and disposal of the system (phase-out).

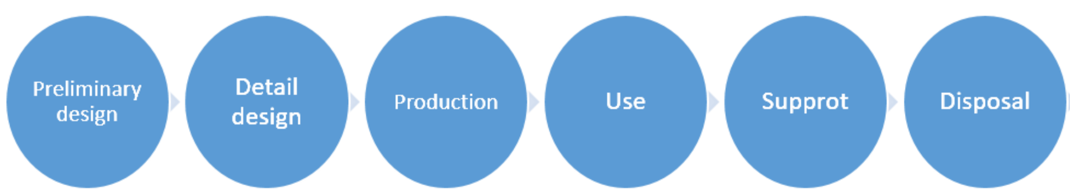

Figure 2-3: Systems life-cycle stages (source: Fabrycky, 2014)

Before the preliminary and detailed design phases of systems engineering for a new system, one should recognize the problems with existing systems, clarify the problems and describe the needs for a new system (Chakravarthy & Krishnamoorthi, 2013). The subsequent action followed by investigating the available data for the existing similar systems in the market and gather as much information as possible. These will help the designer to have a comprehensive understanding of the problem and possible new ideas that would be introduced in conceptualization phase. The values delivered to the customers and stakeholders of a system by the new ideas such as "*better, cheaper, faster*" (E.Cook & A.Wissmann, 2007) should be carefully analyzed in the conceptual phase. An organization may benefit from choosing the right path and building the right foundation in conceptualization phase (by making improvements to the system design) and actions required prior to that (problem and need identification) significantly. These benefits include but are not limited to saving time and money, making breakthroughs in an industry, higher productivity of personnel and better organizational performance, higher product and process quality, and better safety standards.

The variety of the objectives of a new system for their customers lead to think more deeply about the necessity of the system (Eisner, 1998). For instance, different B2B firms in one industry may have different needs for their systems that lead them to different system requirements. An important point to consider is that making a breakthrough and coming up with an invention in industry does not necessarily mean that the idea is innovative. There is a distinction between invention and innovation that if an invention is not successful in the market, it would stay an invention and innovation does not happen (Tidd & Bessant, 2009; Gaubinger, et al., 2015). Thus, the criticality of the problem definition and the need from the point of view of systems engineering is considerable. Due to the focus of the thesis on systematic creativity, ideation phase is discussed in more detail.

2.2.3. Ideation

Within the ideation phase, new ideas will be taken into account and the best feasible ones out of them will be investigated for further development in idea evaluation phase. According to Eversheim (2009), ideation or idea generation consists of two phases:

2.2.3.1. First order product ideas- In this phase, first a comprehensive functional analysis should be implemented to provide a functional model of the system and relationships between components. Second, any novelty at this stage (functional or technological) should be examined by "patent analysis" or "value analysis" to ensure the idea does not exist and the wheel is not reinvented. Third, the ideal product would be imagined by special methods. The usage of methods are continuously over the first phase to form the ideal product and is not cross-sectional. Finally, the ideas are structured by morphological analysis and theoretically accepted ideas are delivered for the second order phase.

2.2.3.2. Second order product ideas- In the second phase, clear and detailed planning of the generated ideas are done. This requires a huge amount of information and research within the organization and outside which can be a time-consuming process because of the quite often non-relevant information acquired. The detailed plan of ideas can then be documented by so-called "*product idea data sheets*" including certain aspects of the ideas such as market issues, organizational considerations and idea description. Only then, one might compare the generated ideas in idea assessment (idea evaluation) and choose the best option from the ideas. A comprehensive feasibility analysis from all perspectives of design, production, maintenance and support is required to reduce the uncertainties that threaten the developing process of the system (Fabrycky, 2014)

B.Magrab et al (2010) consider that there is a distinction between creativity and design methods that support systematic approach to design and classify these methods to six steps of objective clarification, functions establishment, requirements identification, alternatives generation, alternatives assessment and optimization. They also relate creativity to imagination abilities and skills and consider creativity as a "*spontaneous occurrence*". However, the author of the thesis argues that, regardless of whether creative ideas for making radical or incremental innovation are shaped individually or in a group, they could be developed by systematic tools and techniques.

The importance of radical and incremental innovation in a company's survival in today's world was already discussed. Grupp and Maital (2001) believe that making incremental innovation to existing products or services are crucial for a firm and more than 90% of the products that perceived new, are not new concepts and just improvements to the previous versions. The organization culture and "*philosophy"* towards continuous process of making improvements or so-called "Total Quality Management" (TQM) aims at increasing customer satisfaction by involving every individual in the organization in the innovation process (individual tasks or a teamwork) and the proper allocation of resources for innovation purposes (Sorli & Stokic, 2009).

One should be very careful not to misinterpret systematic creativity tools. The methods deployed in industry and research for TQM are different from those for systematic creativity. The methods used for making continuous improvements to the firm are called *Integrated Product and Process Development* (B.Magrab, et al., 2010) and according to their application are divided into three categories: Vertical alignment for high level decision-making in firms, Horizontal alignment for management in the middle level for inter-functional teamwork, and unit improvement for departmental and individual improvements of tasks. These three categories are not completely separate and perceived as complementary for each other while being implemented simultaneously (Sorli & Stokic, 2009). There are various methods and tools used for making continuous improvements to systems. Japanese engineers contributed significantly to TQM by developing various methodologies such as Just-In-Time (JIT) Manufacturing, Kaizen and Lean Manufacturing methods where specific techniques such as Design For Six Sigma (DFSS), Taguchi techniques, Poka-Yoke and Kansei Engineering are deployed for making continuous improvements (Sorli & Stokic, 2009; B.Magrab, K.Gupta, McCluskey, & A.Sandborn, 2010). There are many more techniques and methodologies that support improvements to systems. These include but are not limited to Benchmarking, Quality Function Deployment (QFD) and Quality Cost Control. Systematic creativity is discussed next in more details.

2.3. Systematic creativity

Perhaps the most well-known model for creativity process is the one known as Helmholtz-Poincare-Getzels (HPG) model which was originated in the 19th century by Helmholtz (a German physicist) and Poincare (a French mathematician) and then further developed by

Getzels (an American psychologist). The model consists of five stages of first insight (problem recognition), saturation (data collection to solve the problem and preliminary solutions), incubation (no useful or new idea can be given), illumination (a sudden inspiration on the solution) and validation (organizing the idea to make it presentable). Within the context of engineering design, the most challenging and time-consuming steps are those related to the conceptualization phase. These include saturation, incubation and illumination steps and that is when ideation should starts. There could be many iterations within these three stages (Ogot & Okudan, 2006).

It has always been a challenge whether creativity is an inborn characteristic for human beings or it is acquisitive. A Georgia Tech professor is of the opinion that there are certain methods that can improve problem-solving skills (Ogot & Okudan, 2006), hence creativity can be also acquisitive. Studies in 1960s show that the operation system of a human being's brain is in such a way that the left hemisphere deals with analytical skills and logical thinking whether the right side's task is fast processing, visualization and relating to the previous knowledge. Creativity happens once these two sides can fill the bridge and link to each other and this is exactly the point where creativity tools and techniques can play their role. Despite existing many of them, there is a conflicting characteristics in their nature that they inspire intuition from one hand and organize creativity in a systematic way from another. The role of creativity techniques could be interpreted quite similar to catalyst for a chemical reaction (Gaubinger, et al., 2015).

2.3.1 Brainstorming

It is said that *Brainstorming* is the oldest and the most famous creativity technique which was first presented by Alex F. Osborn. Brainstorming technique consists of two phases. The rules of the first phase are that a group of 4-12 people should generate as many ideas as possible for 20-45 minutes, nobody is allowed to make comments during the brainstorming, using another person's idea for development is allowed and it does not matter if the idea considered to be unrealistic. In the second phase called *SCAMPER*, a checklist for substitution, combination, adaption, modification, elimination and relocation of ideas helps to widen the vision to the problem and ideas and potential alternatives are recognized for further development

(Gaubinger, et al., 2015). SIL (the German acronym for Systematic Integration of Problem Elements) is a similar method to brainstorming that steadily combines many generated ideas to one general solution. It consists of both individual and group works.

The first critique to brainstorming is that the fact that generating more and more ideas in conceptualization without clearly defining the problem (in brainstorming for instance) does not have a proper effect on the results (Salamatov, 2005). Second, the author of the thesis argues that the first phase of brainstorming is not a creativity technique for problem solving, but a method used for group thinking and idea generation. There is no technique or principle that boosts one's brain to be able to come up with new ideas for a specific problem. Therefore, one must be very careful with the terminology used for creativity, since it might mislead the audience. Besides, some methods could be combined in group creativity workshops. For instance, the integration of Brainstorming with Six Thinking Hats could make the discussions wider, from different perspectives and more productive.

2.3.2. Mind-mapping

Mind-mapping is a creativity technique developed from the theory of radiant thinking (Buzan & Buzan, 1996) and deploys graphics, colors tree branches with the major concept centralized for development (Rosciano, 2015). Rosciano's (2015) findings proves that mind-mapping there is a need to take a step away from traditional learning methods such as note-taking, home-works, practical sessions and analysis. Instead, she believes that mind-mapping could be an appropriate alternative students of nursing. Mind-mapping is considered as a suitable tool for the conceptualization phase of a research and supports research methods in many ways (Crowe & Sheppard, 2011). Mind mapping deployment showed success in writing essays and learning foreign languages by decomposing the topics. Furthermore, it made the writing process for students more interesting (Vijayavalsalan, 2016). Mind mapping had proper effects on teaching java programme design course in addition to enhancing students' learning ability (Li, et al., 2015). Not only said to be successful in individual creativity, mind mapping was an achieving technique for collaborative design in a project where multidisciplinary teams interacted (Zahedi & Heaton, 2016).

2.3.3. Axiomatic Design

Axiomatic Design (AD) is a design method used in functional requirements analysis of systems engineering (B.Magrab, et al., 2010) which was first introduced to academia by N.P.Suh in 1978 (Farid & Suh, 2016). According to Suh, the main goal of AD is boosting human being's creativity in design, shortening the random search process, minimizing the iteration and selecting the best design alternatives (Farid & Suh, 2016). To be able to use the method, first functional requirements *FR*s should be clearly defined and decomposed to the smallest independent requirements and design parameters *DP*s should be determined (B.Magrab, et al., 2010). B.Magreb et al. emphasize on that *DP*s should not be confused with the physical product that fulfills the requirement, instead should be able to fulfill the function for *FR*s. For example, if the task is to design a product which provides cold and hot water at the desired temperature and flow rate (should be adjustable), the *FR*s are *obtaining* water flow rate and water temperature respectively, while the *DP*s are the *means to adjust* cold water flow and the means to adjust hot water flow. This is different from the traditional way of thinking that the *DP*s were defined by cold water tap and hot water tap and today's modern tap consists of a handle which can adjust both flow rate and temperature at the required level (B.Magrab, et al., 2010). It is essential to remember that one physical product that fulfills two separate *FR*s independently does not show that the system contains only one DP (indeed, there are two *DP*s as mentioned before and the number of *FR*s are equal to the number of *DP*s).

The method title AD is based on the fact that it consists of two axioms called 'independence axiom' and 'information axiom'. The former determines the independence of *FR*s whereas the latter describes the minimization of the information (Farid & Suh, 2016). The Equation 2-1 describes the complexity level (complexity factor C_f) of a system based on the number of functions f, Constant of convenience K, number of parts N_p, number of interconnections N_i and the number of part types N_t (B.Magrab, et al., 2010)

$$C_f = \frac{K}{f} . N_p . N_t . N_i \ . \qquad (2\text{-}1)$$

The idea behind the AD is a mathematical approach to the design process by matrices theory, which was developed by N.P.Suh. This approach contains a column vector of *FR*s, a column vector of *DP*s and a design matrix [A] with the following relation in Equation 2-2 (B.Magrab, et al., 2010)

$$\begin{bmatrix} FR_1 \\ \dots \\ FR_\mathrm{n} \end{bmatrix} = [A] \begin{bmatrix} DP_1 \\ \dots \\ DP_\mathrm{n} \end{bmatrix}. \tag{2-2}$$

The design matrix [A] itself is a *n***n* square matrix (where *n* represents the number of *FR*s and *DP*s) and A_{ij} may take a value of x showing the dependency between the related FR and DP or the value can be zero if they are independent. For instance, if there are two *FR*s and (obviously) two *DP*s, the design matrix [A] can take the following three forms

$$[A_1] = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix},$$

$$[A_2] = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix},$$

$$[A_3] = \begin{bmatrix} A_{11} & 0 \\ A_{21} & A_{22} \end{bmatrix}.$$

The first matrix $[A_1]$ makes the design more complicated with more information and interconnections (coupled solution) where both *FR*s depend on both *DP*s, the second matrix $[A_2]$ which is a diagonal matrix represents an uncoupled solution where each FR is related to one DP independently and finally the third matrix $[A_3]$ illustrates a decoupled matrix where the both *FR*s are satisfied by DP_2 only. The physical example of $[A_1]$ is using two water taps where opening each causes the change in both temperature and flow rate (impractical). The example of the $[A_2]$ is the traditional water taps (one cold water and one hot water) where opening each results in increase of flow rate in that tap, and finally the example for $[A_3]$ is a modern handle by pulling which the flow rate can be reached at the desired level and turning to the sides causes a change in temperature.

2.3.4. Morphological Analysis

Morphological Analysis MA is a method of problem-solving for complex multi-dimensional and non-quantifiable systems developed by a Swiss astrophysicist Fritz Zwicky. The term *morphology* is a Greek word related to the analysis of shapes, structure of the components in an object and their entire performance as a system (Ritchey, 2011). It is considered as one of the most common creativity techniques which is beneficial for accessing all possible alternatives for problem-solving in addition to the ability of decomposing the system dimensions and values (quality and quantity of ideas) and recombining them in order to achieve creative alternatives. MA has been a wide range of application including scenario development, technological innovation and business models. Furthermore, the literature considering cases where MA has been applied is quite extensive (Geum & Park, 2016).

2.3.5. TRIZ

TRIZ is the Russian acronym of Teorija Reshenja Isobretatelskikh Zadatch and stands for the Theory of Inventive Problem Solving (Altschuller, 1956). Genrich Altschuller was a talented and enthusiastic employee, who first noticed the similar pattern in the evolution of patents. Having extracted and gathered his findings on specific techniques and methods, he wrote many technical solutions and recommendations to academic and industrial organizations.

The main objective in TRIZ is moving towards ideality. Even though it might be practically impossible to reach the ideal illustration in mind, TRIZ makes it possible to make breakthroughs or improvements in systems. Looking at the history of systems evolution confirms that all systems have been developed to some degree of ideality (Salamatov, 2005). For instance, let us consider the actions required to fulfill the function of removing dirt from clothes. The most recent available technologies designed in such a way that remove the dirt from clothes by using a washing machine and detergents. However, ideally, dirt should not stick to clothes or clothes can remove dirt themselves (Mann, et al., 2011). The objective of the concept of IFR is to use as less resources as possible and the best idea is to make the system self-function and use the least amount of resources. The Figure 2-4 gives a better understanding of the IFR concept.

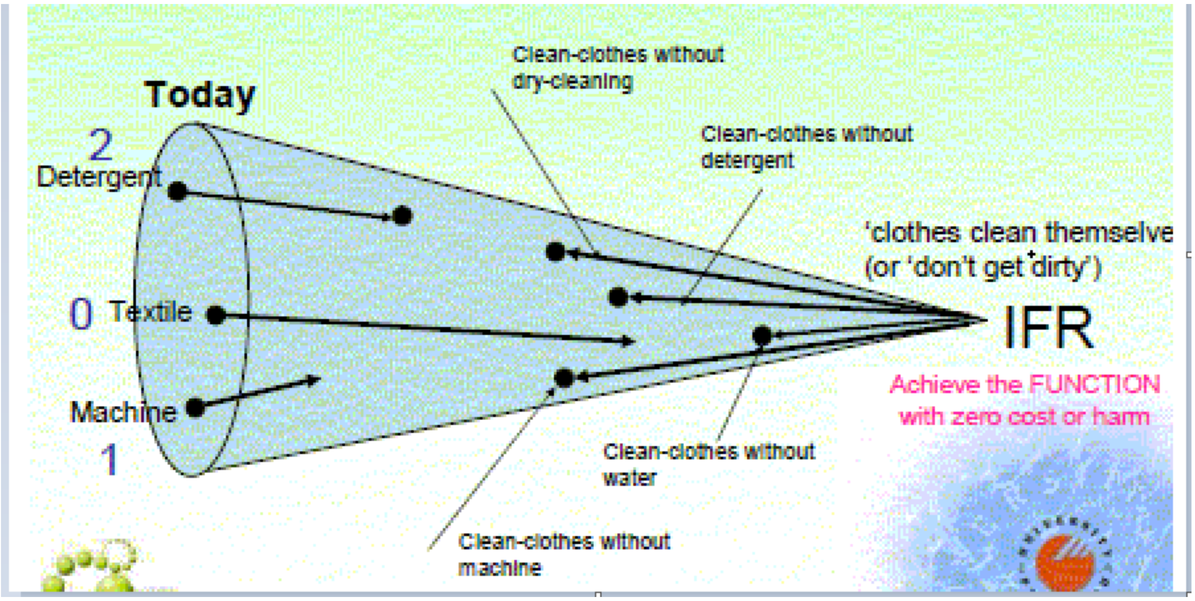

Figure 2-4: The IFR for washing clothes (source: (Mann, et al., 2011)).

2.3.5.1. TRIZ principles

The approaches used in the theory of inventive problem solving are categorized to standard procedures and Algorithm of Inventive Problem Solving (with the Russian acronym of ARIZ). These two approaches are usually combined over the process of inventive problem solving (Salamatov, 2005). The emphasis in standard procedures is elimination of contradictions, which in turn could be divided to technical and physical ones. The foundation of TRIZ principles were built by Altschuller by discovering 39 technical contradictions while analyzing patents in former Soviet Union. He then came up with 40 principles to eliminate these technical contradictions from systems. The technique is that technical characteristics of products shape a square matrix of 39 by 39. When these cross each other (means there is a contradiction between the two technical characteristics), solutions (40 principles) could be used to eliminate the contradiction from the system (Altschuller, 2001). Physical contradictions elimination is another technique in TRIZ where separation is the solution to the contradiction. It is when a property of a system has two be of two opposite or contradicting situation for different grounds. For instance, a product should be heavy based on one reason but should be light for another reason. These contradiction could be solved by separation in time, space or condition. This technique could be used for non-technical issues such as in strategic decision-making for acquisition of a company where the fear of information leakage and contamination requires the separation of acquisition team from the normal office.

Apart from contradiction elimination and IDF, there are many more techniques used in TRIZ deploying which could result in inventions. These techniques include but are not limited to Function-Oriented Search (FOS), Cause and Effect Chain Analysis, system evolution prediction and more. Trimming is a famous technique used to approach ideality by maintain the system functionality. Trimming is classified into three categories of device, process and organizational trimming. Trimming could be implemented on a system level where the components of the system are considered for trimming or a super-system level where the surrounding environment's interaction with the system components are also taken into account. It is proved that trimming has got a wide range of application. For instance, it has been used for patent design and prevention of patent infringement (Li, et al., 2015) or solving the problem of a slit-valve in semiconductors.

2.4. Compatibility of the theoretical framework with the research

The theoretical part of the study consisted of three chapters, each including different subchapters and concepts. It is important to understand how the literature can support the study in terms of filling the research gap and fulfilling the objectives of the thesis. Therefore, below, each chapter and their contents are discussed individually to better explain the links to the problem.

The main objective of the study is to understand the effect of mathematical modelling on radical innovations in chemical mixing industry. Therefore, it was important to discuss the concept of "Innovation Management" at the initial pace. To be able to totally comprehend the concept, one should realize the real definition of innovation and how it is different from invention and creativity. It was also essential to realize the major drivers of innovation in today's competitive markets, the origins of innovation, different level and categories of innovation. These were all crucial to understand the objective and what type of innovation is satisfied by the empirical study and is the target of the thesis.

As the RQ1 considers a chemical mixing process and the goal is to discover creative ideas that result in radical innovation, the different parts of the mixing process should be considered as the system elements. Therefore, another important piece of the theoretical part to consider was systems engineering. One was supposed to have a sufficient level of knowledge in systems, their taxonomy, lifecycles and different stages.

The link between the first and the second subchapter is the ideation phase of systems engineering, where the process and its results are directly related to the innovation process of a firm. Within this phase, novelty and newness appears in the firm's activities and the potential ideas are evaluated further. The ideation phase and systematic creativity were included in the literature review, because they are deployed in the empirical study, where mathematical modelling is the systematic approach towards innovation in mixing process within the ideation phase. The principles of one of the most well-known and successful creativity techniques for radical innovation, TRIZ, were included in the theoretical part of the study. Also, in the vein of using math's for radical innovation, the concepts of AD and Morphological Analysis were shortly discussed. One may argue that the theoretical part lacks the concept of mathematical modelling. The reason behind this action is that mathematical modelling in the existing literature is used for optimization in many fields of science, but not mainly as the means for making breakthroughs in industries.

Symbols

$C_{f,}$ Complexity factor of a system

f, Number of functions of a system

K Constant of convenience of a system

N_i Number of interconnections

N_p Number of parts of a system

N_t Number of part types

3. EMPIRICAL STUDY

The empirical part of the thesis follows the general procedure of systems engineering and is divided into three main stages. Within the first and second stages, an overview of chemical mixing process is presented, the problem is recognized and preliminary solutions studied by Yakovis and Chechurin (2017) are demonstrated. The third stage is devoted to the ideation phase where new ideas by mathematical modelling are introduced.

3.1. Industrial mixing process

Mixing is the *"intermingling"* action of two different materials in order to achieve a certain "*level of uniformity"* in the mixture and perceived as the most common process in chemical industry (Holland & Chapman, 1966). Mixing process is one of the crucial steps in many industries including food, paper and pharmaceutical where physical and chemical changes affect the process (Harnby, et al., 1985). Despite its importance, the existing knowledge in mixing process is not comprehensive yet and lacks the proper design codes (Harnby, et al., 1985). Mixing process could be analyzed from the point of view of the phase of the materials to be mixed (solid, liquid or gas), miscibility, suspension, mixing purposes, mass transfer or chemical reaction. In liquid mixing, similar to many other fluid regimes, the process can be either laminar or turbulent (Harnby, et al., 1985).

The selection of existing mixers in the market for a specific process depends on the function that they fulfill (such as miscible liquids blending, emulsification processes and suspension), controlling factors (such as heat removal and addition), process requirements (such as material corrosion) and the materials characteristics (such as being shear-sensitive or not). In general, mixers could be classified into mechanically-agitated systems, jet mixers, in-line mixers (static and dynamic), valve homogenizers, ultrasonic homogenizers, extruders and dispersion mills. Each of the mentioned categories can be divided to many subcategories with various shapes and design characteristics (Harnby, et al., 1985). The Figure 3-1 depicts a continuously stirred tank reactor used for a non-adiabatic process (Mathworks, 2016). The first part of the empirical study is based on a study on cement production industry. However, in order to make the study simpler and develop more and better ideas, the mixing system that would be taken into consideration for conceptualization phase of this study is the mechanically-agitated systems for blending single-phase miscible liquids. This system consists of a vessel (tank), where liquids are continuously stirred by an impeller and baffles are deployed to prevent possible vortex in the system (Harnby;Edwards;& Nienow, 1985).

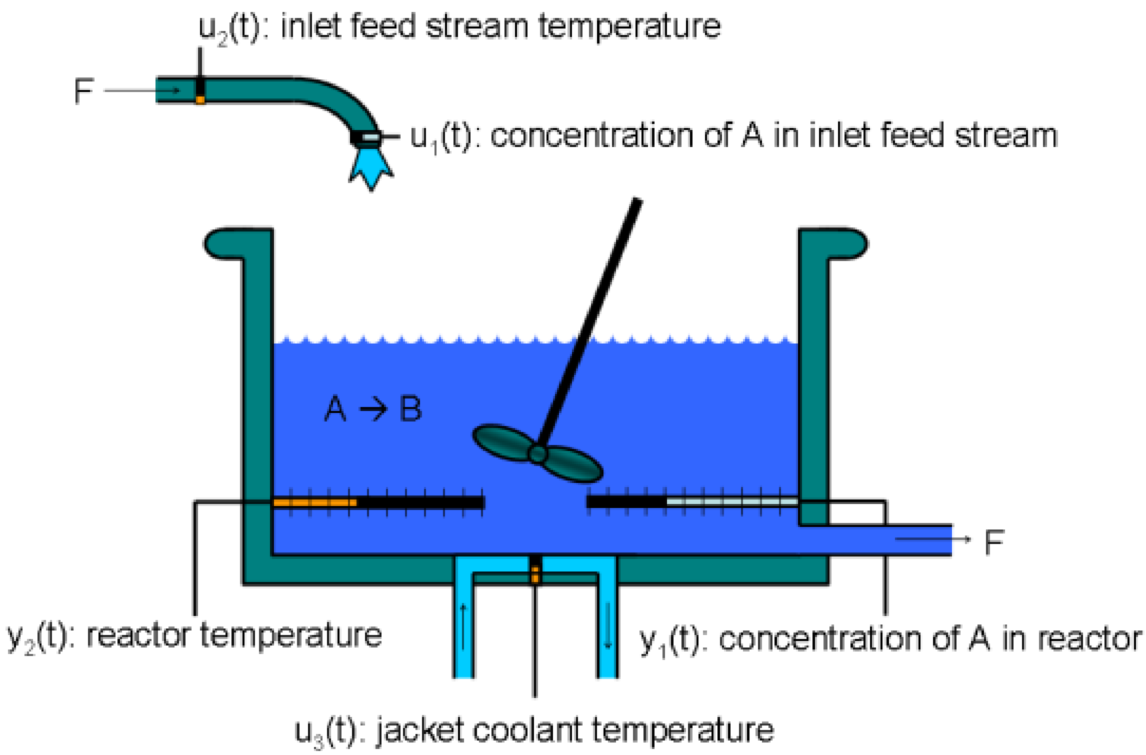

Figure 3-1: Non-adiabatic Continuously Stirred Tank (Source: Mathworks, 2016)

There are various types of impellers to be used for mixing process including propellers, turbines, anchors, paddles, helical screws and helical ribbons (Holland & Chapman, 1966; Harnby, Edwards, & Nienow, 1985). The required type of impeller is determined by the liquid viscosity (Holland & Chapman, 1966). Propellers, turbines and paddles are the ones that mix liquids of low viscosity and work at high rotational speed. The higher the viscosity of liquids the larger would be the size of impellers (Harnby, Edwards, & Nienow, 1985).

There exists a range of problems and difficulties in mixing process. As it pertains to immiscible mixing, high contact area between liquids are required. For emulsions, the mixture is quite stable and segregation takes a very long time then. Furthermore, the viscosity of the emulsion would be quite high. One should be very careful in that overmixing may result in deterioration of the quality of the mixture or excessive consumption of energy (Harnby, et al., 1985). Considering the existing problems in conventional mixing process in details is out of the scope of this study. However, since the focus of the case study is the blending system of single-phase miscible liquids, the problems related to this this process is taken into account for conceptualization phase.

One of the most important points to be borne in mind is the analysis of energy consumption for mixing process. Although this analysis could be very complicated and in many situations these analysis are based on experiments, some factors could provide an approximate energy consumption calculations. The viscosity of the liquids and the fluid (liquid in this study) type in terms being Newtonian or non-Newtonian may affect the energy consumption significantly. In case of high viscosity liquids, the equipment power for mixing process is far higher and consequently the energy consumption would be more. If the liquids are non-Newtonian, the estimations become more and more complex (Harnby, Edwards, & Nienow, 1985). The detailed study of equipment power for mixing process is out of the scope of this study, but investigated for a continuously stirred tank containing Newtonian liquids in brief. According to Harnby et al. (1985) the factors influencing the ideal equipment power are liquid density ρ, liquid viscosity μ, impeller diameter *D*, impeller rotational speed *N*, Tank diameter *T*, impeller width *W* and liquid depth *H*. Needless to say is that these factors are not all one needs for power calculations and there are more parameters for this purpose. Besides, the abovementioned parameters are used to calculate the ideal power for mixing and losses by motor, gearbox and bearings should be also taken into account. The fluid mechanics analysis of this process is too complicated because of the geometry complexity of the equipment, vessel and heating coils. Having simplified the process by dimensional analysis, the power consumption could be described by the Equation 3-1

$$\frac{P}{\rho N^3 D^5} = fn\{\frac{\rho N D^2}{\mu}, \frac{D N^2}{g}, \frac{T}{D}, \frac{W}{D}, \frac{H}{D}, etc\}. \tag{3-1}$$

The left side of the equation refers to the Power Number P_o and the first two parameters of the right side of the equation describes the Reynolds number and Froude number respectively. In most cases, either the Froude number is neglected or its effect is eliminated by using baffles.

Thus, the power number could be considered as a function of the Reynolds number in similar systems. Different speeds of the impeller, liquid density and viscosity in a system with given geometric parameters could provide a power curve where the variations of the Reynolds number (axis X) and its impact on Power number (axis Y) are projected. For different power curves for different impellers geometries can be found in the existing literature. The power usually required for blending low viscosity liquids (Newtonian liquid) is 0.2 kW/m^3 whereas the power consumption in blending pastes and doughs are almost 4 kW/m^3. This example was set just to show how the density and viscosity of the material might influence on power consumption. The major question remaining here is the required rotational speed of the impeller, which in turn changes the required power. The answer to this question, however, needs a detailed investigation of the process in terms of mass transfer. The information provided by power consumption helps in turn to determine the motor selection and shaft and gearbox design (Harnby, Edwards, & Nienow, 1985).

Another important indicator of a mixing process is the mixing time which is the duration of time between the addition of liquids to the point of time where the required level of uniformity is met. For a single-phase miscible blending process of liquids (liquids with similar density and viscosity), the variations of concentration is measured continuously and recorded until the certain level of equilibrium concentration is reached. This equilibrium point could be calculated by knowing the volume of the liquids. The method of addition, the location of the measuring detector and number of records in the tank affects the mixing time. Similar to power consumption calculations, mixing time is a function of rotational speed of the impeller and Reynolds number with the following relationship in the Equation 3-2 (dimensional analysis)

$$t_{\mathrm{m}} = f(N, Re). \tag{3-2}$$

In a single-phase miscible blending process of liquids, the tank application is important in that whether the mixing process is on line (being as a part of a production process, sometimes called inline or pipeline mixing) or off line (storage tanks) which in turn influences the frequency of tank filling and emptying. One important point to notice here is that the wide difference between the liquids viscosity and density results in high-energy consumption of the impeller. The borderline for the differentiation of low against high viscosity is 50,000 centipoise that results in using different impellers for mixing process (McDonough, 1992). Another problem is that if the share of one of the liquids is too small, the process is not easy any more (Harnby, et al., 1985) and more energy is consumed for this type of blending process (McDonough, 1992). The next issue is the state of the agitator being on or off while adding components. It can prolong the blending time significantly if the agitator is not operating while the addition. On top of that, apart from the time restrictions in blending process (process requirement), the degree of quality and uniformity of the mixture is also one of the indicators that influence the process time and quality. Another important point is that the bigger the dimensions and volume of the blending tank, the more energy is required for the process. Mechanical failure of the system might impose huge expenses for the users (such as the loss of "*liquor*" (vessel content), spare parts replacement and labor costs). Last but not least, the speed of the impeller might affect the thermal qualities of the mixture. The Figure 3-2 illustrates the problems associated with the blending process of single-phase liquids using mechanical agitators. Overall, financial benefits are achieved by saving more energy (operational costs in general) and decreasing capital costs (McDonough, 1992). This could be a ground for considering the process with new opportunities in macro-scale economy (Harnby, et al., 1985).

Figure 3-2: Influencing parameters on blending process of single-phase liquids

3.2. Problem recognition and preliminary solutions

The conventional methods of mixing processes impose high expenses for the firms involved in chemical industries (Yakovis & Chechurin, 2017). The major function of the mixers in single-phase liquid blending is homogenization of the mixture in such a way that the deviation of the liquor concentration be minimized. The problems of the mechanical agitators that mentioned in the previous subchapter might lead one to think about performing the same function with new ideas and possibilities to reduce or eliminate those detrimental impacts. Static mixers for inline mixing is an example of the idea to fulfill the function in a pipeline. For instance, they can be used for heating process when adding steam to a process, blending or pH control. A static mixer is made of a pipeline and stationary components that cause laminar or turbulent flow in the pipeline (McDonough, 1992). According to McDonough (1992) there are benefits and drawbacks in using static mixers. In comparison with mechanical agitators' capital costs, operational costs and residence time are lower in static mixers, maintenance is easier and flow and shear is more controllable. Yet, mechanical agitators are more adaptable to mixing process and the range of application of mechanical agitators are wider than static mixers. The Figure 3-3 illustrates a modern static mixer used for pipeline mixing. There has always been efforts to make improvements to industrial mixers by "*retrofitting*" them (McDonough, 1992). Less attention has been paid to the concept and make radical changes to industrial mixers, however. The subsequent subchapters are devoted to new ideas that recently turned up and its development in the thesis.

Figure 3-3: Static mixer (source: Koflo)

The conventional mixing process (by using tanks and impellers) is compared to an idea in mixing process (Yakovis & Chechurin, 2017) where impellers are eliminated from the process. Both methods are simulated and compared by using Simulink and required values of the process. Moreover, the idea is further developed by incorporating active control over inflow. Also, a new idea of simultaneous dosing and mixing is introduced.

In the mathematical analysis of (Yakovis & Chechurin, 2017), they managed to eliminate impeller from mixing process but still keeping its function (averaging the mixture and decreasing the variation at the required concentration of outflow) in force. In order to compare their method with the conventional mixing process using impeller, both methods should be analyzed. In the first step, let us focus on the conventional mixing process with impeller and averaging tank:

3.2.1 Mixing process with an impeller and averaging tank

According to Yakovis and Chechurin (2017), in order to find the volume of the mixing tank, the following equations were used

$$\frac{d\alpha}{dt} = \frac{1}{T}(\alpha_{\text{in}} - \alpha_{\text{out}}), \tag{3-3}$$

where α_{in} and α_{out} are the percentage concentrations in inflow and outflow respectively and T is the tank filling time. To solve the differential equation, the following convolution and weighting function are used

$$\alpha_{\text{out}} = \int_0^\infty h(\theta)\alpha_{\text{in}}(t-\theta)d\theta, \tag{3-4}$$

$$h(\theta) = \frac{1}{T}e^{\left(-\frac{\theta}{T}\right)} \ . \tag{3-5}$$

Considering the fact that the inflow concentration deviation is stochastic with the subsequent equation showing the autocorrelation in inflow concentration deviation, (ζ represents the frequency of change in inflow concentration),

$$r(\theta) = D_{\text{in}}e^{-\zeta|\theta|} \ , \tag{3-6}$$

the deviation in outflow using the following equations was found by the Equation 3-7,

$$D_{\text{out}} = \int_0^\infty \int_0^\infty h(\theta_1)h(\theta_2)r(\theta_1-\theta_2)d\theta_1 d\theta_2 \ , \tag{3-7}$$

or

$$D_{\text{out}} = D_{\text{in}}/(\zeta T + 1) \ . \tag{3-8}$$

Let us show the mass flow rate and mixing material mass by Q and P respectively. Then, knowing that mass equals to the product of mass flow rate by the tank filling time T, the equation (3-8) can be replaced by the Equations 3-9 and 3-10 respectively

$$D_{\text{out}} = D_{\text{in}} Q/(\zeta T + 1), \tag{3-9}$$

$$P = \left(\frac{Q}{\zeta}\right)\left[\frac{D_{\text{in}} - D_{\text{out}}}{D_{\text{out}}}\right] \; . \tag{3-10}$$

Having determined the required averaging factor of mixing process η (which in turn is defined by the ratio of mean square error in outflow to the one in inflow) which is usually set by the client or process codes and standards and replacing the values in (3-6), the mass volume of the mixture would be found through the equation (3-11),

$$P = Q/\left[\, \zeta \left(\frac{1}{\eta^2} - 1\right)\right] \; . \tag{3-11}$$

Simulation

In this part, the result of simulations by using Simulink for each part is shown. In order to be able to compare the methods of mixing process, numeric calculations and simulations of them required. Here, the following parameters were taken from an industrial mixing process. The same values will be used for the subsequent calculations in other methods.

ζ =0.3 h^{-1}

η = 0.24

Q = 100 *tons/h*

C_{req}= 0.5

0<C_{in}<1

Where C_{req} is the normalized required mixture concentration in outflow and C_{in} is the normalized range of deviation in inflow concentration. By replacing the abovementioned values in the Equation (3-11),

$$P = 20.374 \; tons$$

For this case, P shows the total mass of the inflow materials, from which one might calculate the volume of the liquids and consequently the tank volume by using the material density (not used in this study). Since the mixing process is dynamic, it should be analyzed by differential equations to describe the behavior of the system over time. The Figure 3-4 depicts the block diagram of the conventional mixing process in Simulink to project the mixing process by using an ideal impeller, where the mixture is perfectly homogenized. Instead of the required differential equation, the transfer function (Laplace transform of the equation) of the first order is used, where the coefficient of the denominator is the projection of the mass volume.

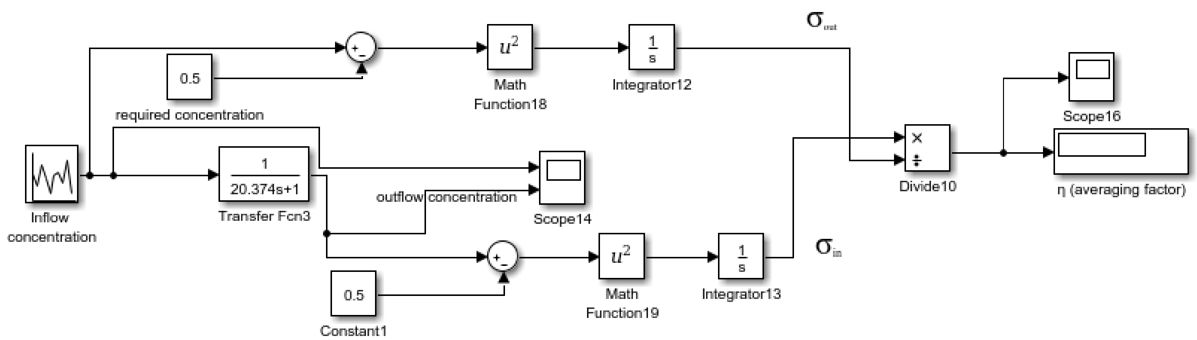

Figure 3-4: Mixing process block diagram (using impeller)

As can be seen in the model, the stochastic process (the illustration of concentration deviation in inflow) that acts as a disturbance to the system is given to the transfer function and the efficiency of the mixing process is then measured by the coefficient η. The stochastic signal minimum and maximum values are 0 and 1 respectively while 0.5 is the assumed required concentration in outflow (normalized deviation). The Figure 3-5 depicts the stochastic concentration deviation in flow over time (in a short period to give the notion of the deviation pattern). The simulation time was assumed 1000 hours to see the behavior of the system clearly over time. Below, the simulation of input and output signals are demonstrated.

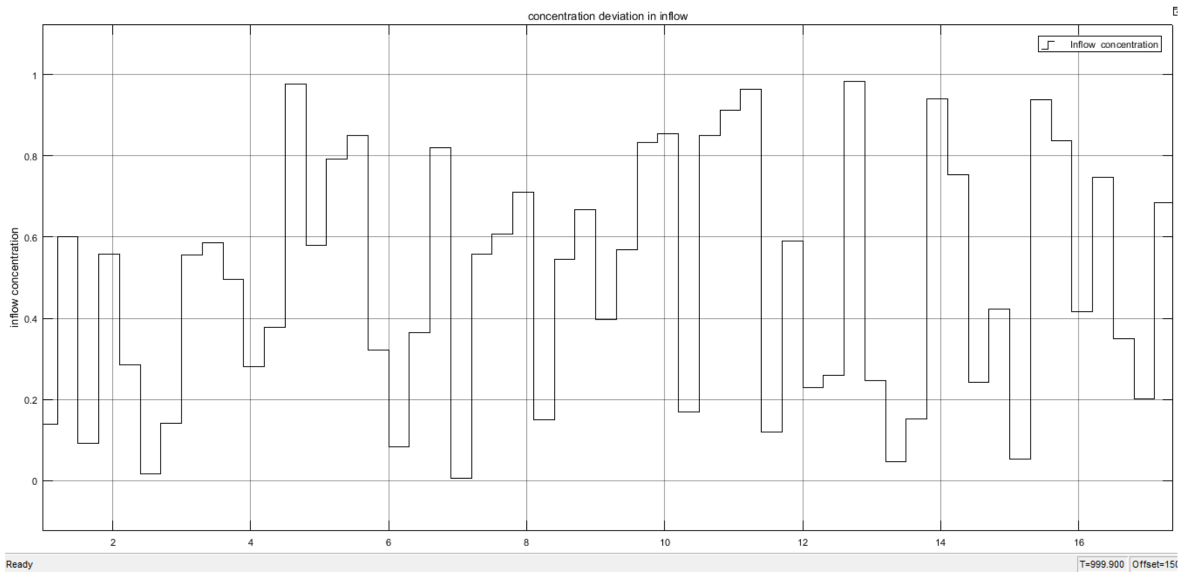

Figure 3-5: A view of the stochastic concentration deviation in inflow

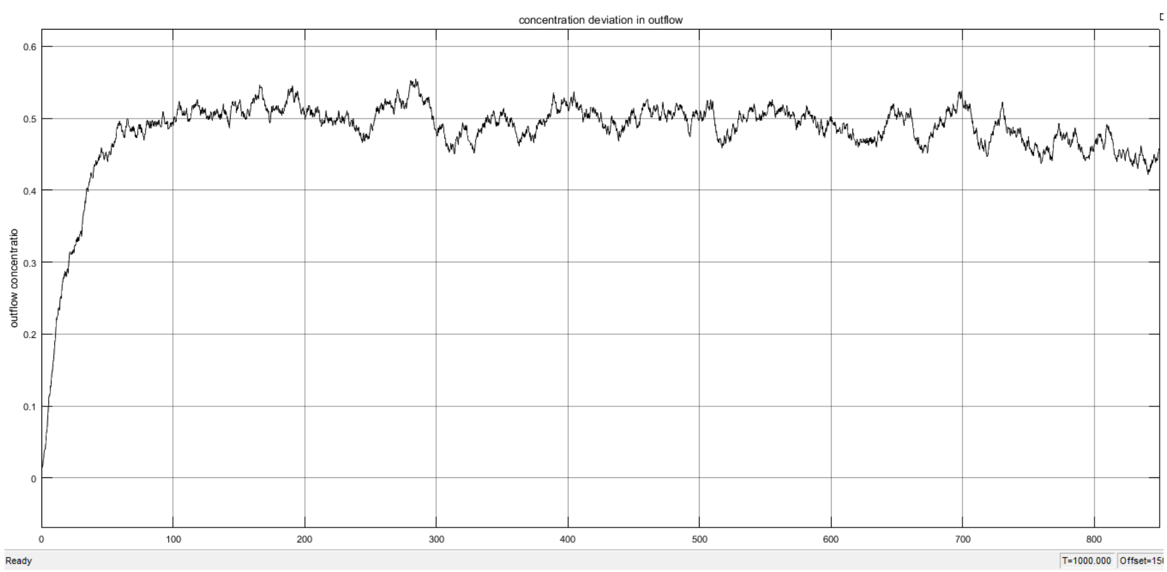

Figure 3-6: Outflow concentration deviation (using impeller and tank for mixing)

As can be seen in the Figure 3-6, the concentration of the outflow rises in the first 150 hours until it reaches the stationary concentration level (0.5) and then it slides over this value. One might argue that this duration of time (the first 150 hours) must not be considered in the analysis of dispersion in the outflow because it makes the calculations unbiased. However, this does not affect the results significantly over a long time, where the ratio of area blockaded between the exponential part of the diagram and *y*=0.5 is not that big to influence the results notably. The difference between the two integral calculations affects the coefficient η by less than 0.01 in total over 1000 hours (it changes because the input signal is stochastic, but the value is less than 0.01 in all trials) and thus is neglected. The changes in simulation time to the *growth of the integral value* can be considered as an exponential function of $G(t) = e^{-t}$ where the integral growth $G(t)$ approaches zero after a certain duration of time. Therefore, the question of whether to consider the exponential part of the function in calculations or not depends on the mixing process time restrictions, usually set by either clients or chemical process codes standards.

Another point to consider is that the coefficient η cannot be calculated by the ratio of integrals of the output. The longer becomes the simulation time the bigger the value of the integral from input is, because the deviation is quite the same over time. Yet, the integral of the output (concentration deviation in outflow) becomes more stabilized after 150 hours. Thus, to make the calculation independent from time, the ratio is calculated by the slope of rise in outflow concentration deviation to the one in inflow. In Simulink, it is done by simply dividing the final value of the output in the end of the simulation by the final input value at the same time. The Figure 3-7 shows the slope of the rise of the integral in Inflow and outflow concentration deviation.

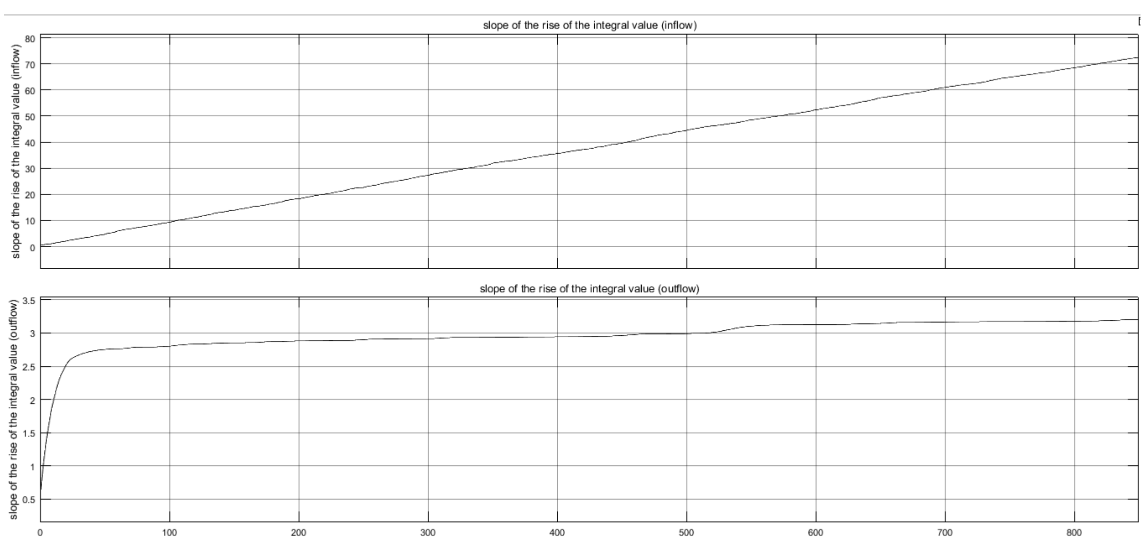

Figure 3-7: slope of the rise of the integral in Inflow and outflow concentration deviation

3.2.2. Mixing process without an impeller by passive control over inflow

Let us now briefly investigate the inventive idea by Yakovis and Chechurin (2017) for mixing process. The idea is to eliminate impeller from mixing process and thus, homogenization process is performed by means of using no impellers, yet the function of homogenization is fulfilled (which is the illustration of the Ideal Final Result). The general idea is to divide the inflow to N portions (without considering the direct flow from the main pipe to the tank), delaying each portion according to the frequency of changes in concentration (the period) and then send the content to the tank.

The flow rate in each portion could be different from the others and it affects the delay time for the portion. In this study, for simplification purpose, it is assumed that the volumetric flow rate in all portions are the same. Therefore, the mass flow rate in each portion equals to the division of the total mass flow rate by $N+1$. In this step, the simulation of this idea within the same mixing process is provided. All the parameters are the same, but no impeller is involved in the process. Instead, the inflow liquid is divided into $N+1$ portions. Theoretically, it is assumed that the higher the number of portions containing the inflow liquid the lower would be the value of coefficient η and the less is the deviation in outflow concentration. On the other hand, it is not realistic to divide the inflow to infinity portions in practice. The question that what the minimum number of portions needed to enable one to reach the required value of η (the maximum allowed η) is, could be of a great interest to solve in further research. The Figure 3-8 represents the mathematical model developed by Yakovis and Chechurin (2017) which in turn depicts the innovative idea of lessening the averaging factor by just giving delays to the portions and eliminating the impeller.

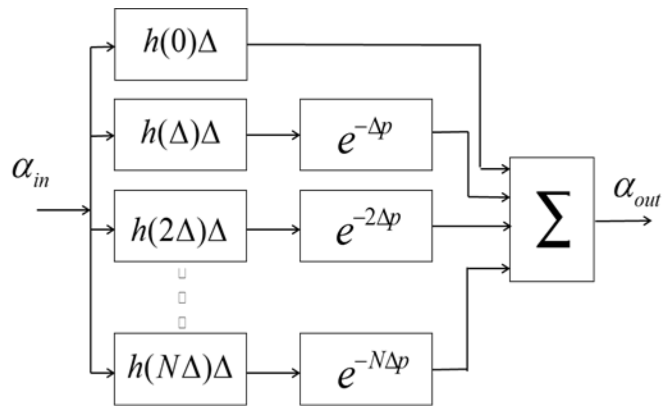

Figure 3-8: Mathematical representation of the innovative idea by Yakovis and Chechurin

Simulation

The assumption is that by dividing the inflow into more and more portions, the averaging factor should improve. Here, the simulation is done by trial and error method to see what the minimum number of portions is. The Figure 3-9 depicts the block diagram of the simulation in Simulink by dividing the inflow into four portions. Due to spacing restrictions, the block diagrams of the higher number of portions are not shown here.

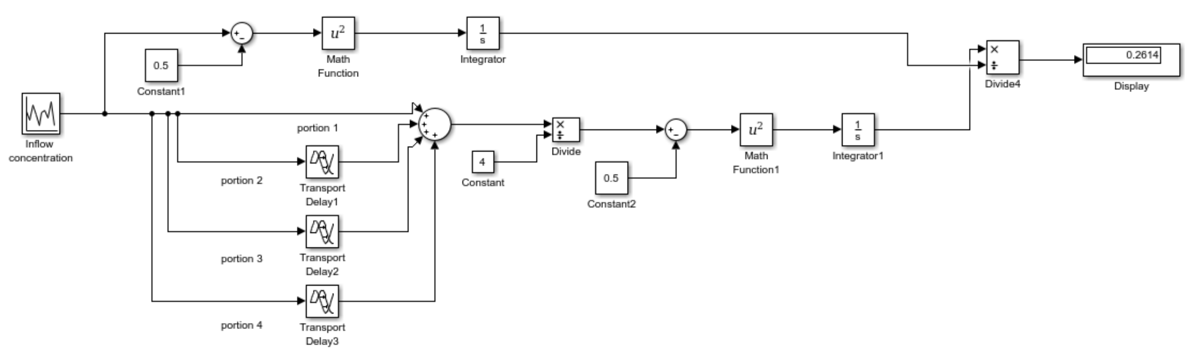

Figure 3-9: Block diagram of dividing the inflow into four portions and delaying portions

Quite the same as the simulation in the previous section, the dispersion is calculated using the same method. The delay at each portion equals to the change period (frequency reciprocal) multiplied by the portion order. For instance, in the above diagram, the first portion is directly sent to the tank (no delay), the second portion is kept for $3\frac{1}{3}$ h (because the frequency of concentration change is 0.3 h^{-1}), the third portion delays at $6\frac{2}{3}$ h and finally the fourth portion should be sent to the tank after 10 h from the beginning. The Figure 3-10 represents the deviation of the outflow concentration by dividing the inflow into six portions and delaying portions.

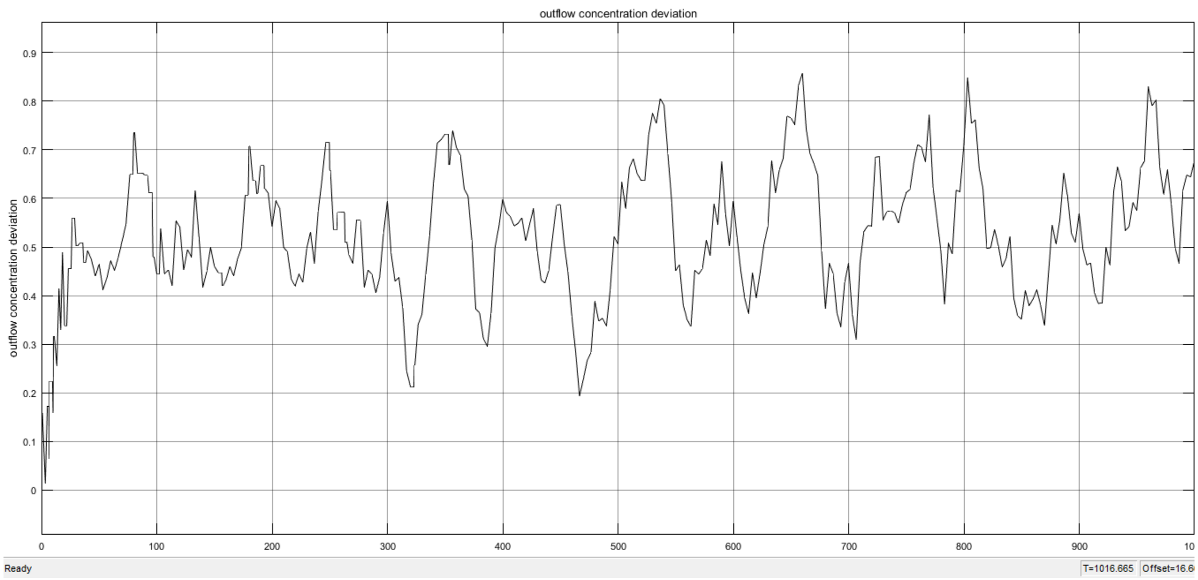

Figure 3-10: outflow concentration deviation by passive control over inflow

The Table 3 shows how the change of number of portions influences on the averaging factor. In order to avoid bias in the experiments and minimize the error, each experiment is done for five times and the average value is taken out for further analysis. In this trial and error experiment, the minimal number of portions required to reach the maximal allowed averaging factor (0.24) is six. Although by using five portions the required averaging factor could be reached, it is recommended to use six portions to minimize the risk as it might still be possible to see a value more than 0.24 by using five portions. The Figure 3-11 illustrates the change in averaging factor considering the average values.

The very same bias issue experienced in the previous task could be argued for this analysis as well, because the output concentration rises exponentially in the beginning till the last portion is added to the container when it stabilizes and slides over the required concentration. Thus, the response to the question whether to take this part of the simulation into account or not is upon the client requirements and time restrictions.

Table 3-1: The influence of changing the number of portions on the averaging factor

number of pipes	delay time (h)	Time (h)	Experiment					average
			1	2	3	4	5	
1	0	1000	1	1	1	1	1	1
2	$3\frac{1}{3}$	1000	0.567	0.555	0.561	0.558	0.546	0.56
3	$6\frac{2}{3}$	1000	0.387	0.365	0.388	0.351	0.389	0.38
4	10	1000	0.247	0.312	0.276	0.255	0.289	0.28
5	$13\frac{1}{3}$	1000	0.226	0.199	0.196	0.21	0.221	0.21
6	$16\frac{2}{3}$	1000	0.189	0.21	0.185	0.174	0.162	0.18

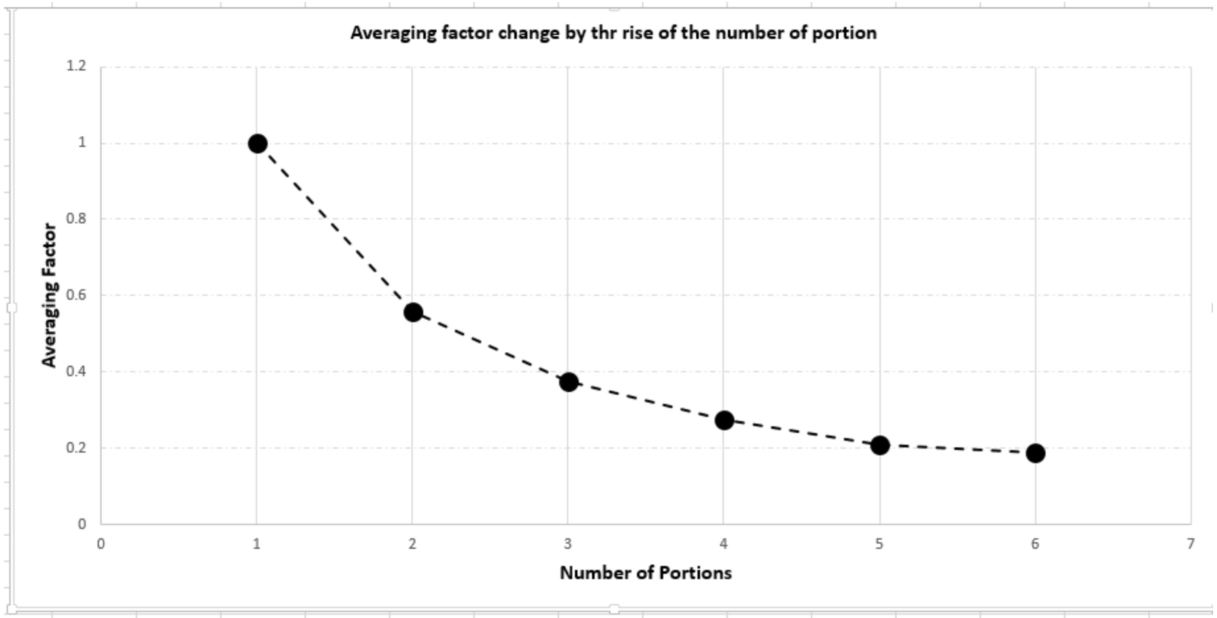

Figure 3-11: averaging factor change by the rise of the number of portions

3.3. Ideation

In this subchapter, based on the results of the simulations from the previous subchapter, new ideas shaped by mathematical modelling are scrutinized.

3.3.1. Mixing process without an impeller by active control over inflow

Now let us look at the situation from a different point of view. In the previous stage, the action was just dividing the content into equal portions and delaying each portion based on the sample time (the period of change). Within this stage, an active control over the inflow is investigated. First, based on the required accuracy of the process (by means of averaging factor and time to be set by client or process standards) the content is divided into different groups. The criterion for classification of the content is the range of the normalized inflow concentration deviation. The idea in this section is to combine the groups that are symmetric to the value 0.5 together after the required delay. The assumption is that the more groups and divisions are implemented in inflow the lower averaging factor would be achieved.

In order to examine the assumption, there would be three different experiments at this stage with divisions to 4, 8 and 10 groups. To make the division and groups clear, let us consider the experiment with 10 groups. The inflow is classified into 10 groups by the normalized range of 0.1, which means that the normalized difference of concentration deviation between minimum and maximum values in each group is 0.1. The Table 4 is an illustration of the classification base (by the range) and the combination base of the groups (using the same color of the groups to be combined).

Table 3-2: Classification of the inflow and combination of the groups

Group number	Normalized concentration deviation range	color
9	0.9-1	
7	0.8-0.9	
5	0.7-0.8	
3	0.6-0.7	
1	0.5-0.6	
2	0.4-0.5	
4	0.3-0.4	
6	0.2-0.3	
8	0.1-0.2	
10	0-0.1	

It means that, for instance, any inflow concentration ranged between 0-0.1 or any inflow concentration between 0.9-1 are assigned to groups 10 and 9 respectively. It means that there would be in total five combinations including groups 1 and 2, 3 and 4, 5 and 6, 7 and 8, and finally 9 and 10.

Simulation

The projection of the abovementioned idea in Simulink is a bit more complicated than the previous one. Thus, here, a brief explanation of the simulation methods and the required mathematical analysis are provided. The modelling of this idea should be divided into three parts including two Simulink models and a MATLAB code, where the aim of the first model and the code is providing the required values for the analysis in the last model.

1. The inflow concentration (input signal in Simulink) is divided into the ten groups with the characteristics mentioned before and the model is run to achieve the values needed from each group. A schematic view of the model is provided in Figure 3-12.

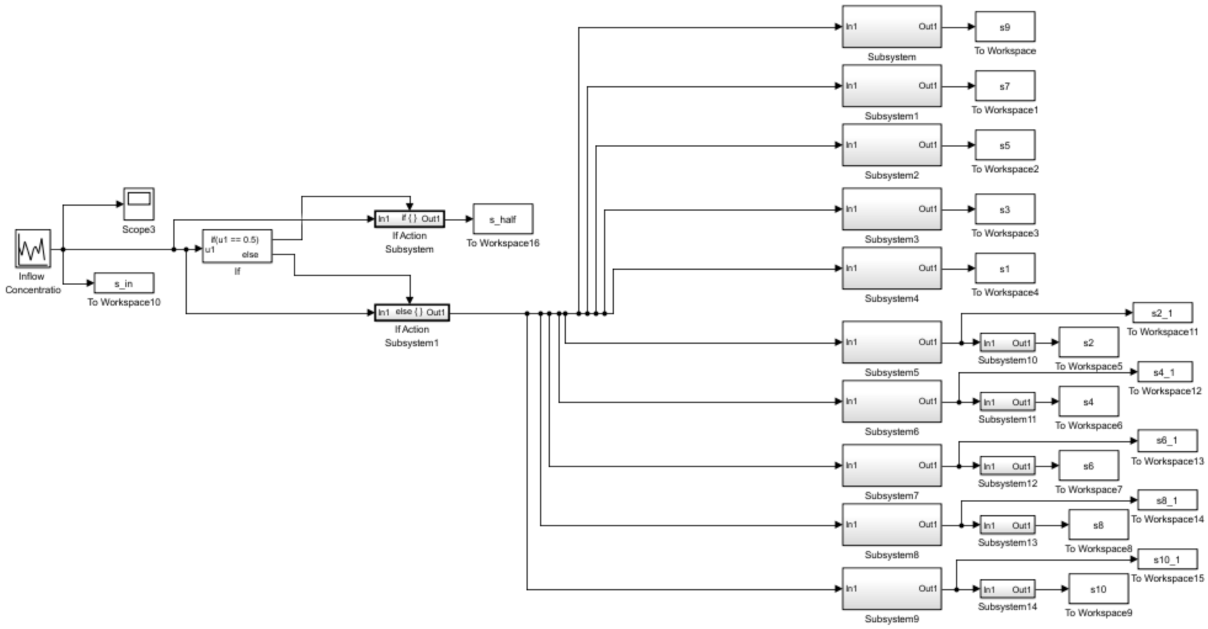

Figure 3-12: The first Simulink model for active control over inflow to produce signal values

The values in each time execution are different because the process is stochastic. The produced values from each group are assigned to the related variables. To make it clear, the signals from the groups 5 (0.7-0.8) and 6 (0.2-0.3) are demonstrated in the Figure 3-13.

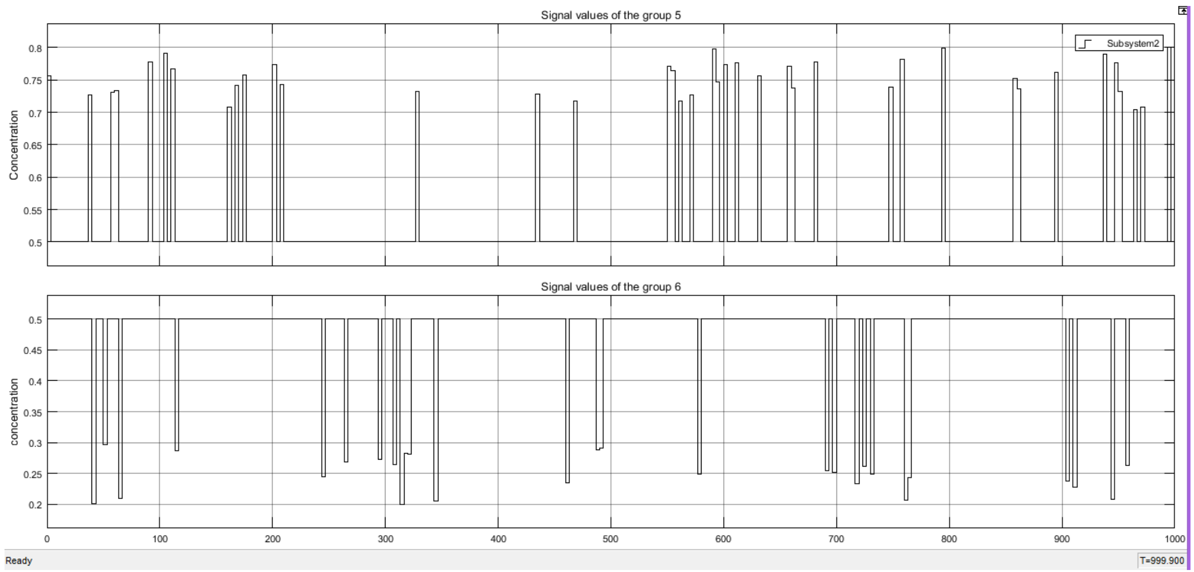

Figure 3-13: Signal values of the groups 5 and 6

Now that the required values are provided, for further analysis, additional values and variables are needed. Let us subtract the signal values of the group 6 from the constant 1 and find the absolute values of them. In fact, it means to flip the model of the group 6 around (rotate the model 180˚ around the axis *X*). The figure 3-14 shows the required calculation to be done on signals 2,4,6,8 and 10 while the figure 3-15 depicts the signal of group 5 against the recalculated values of signal 6

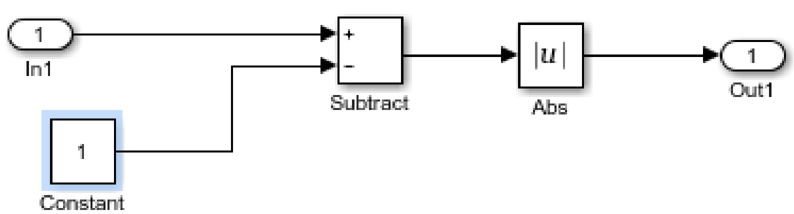

Figure 3-14: Required calculation for signals of the groups 2,4,6,8 and 10

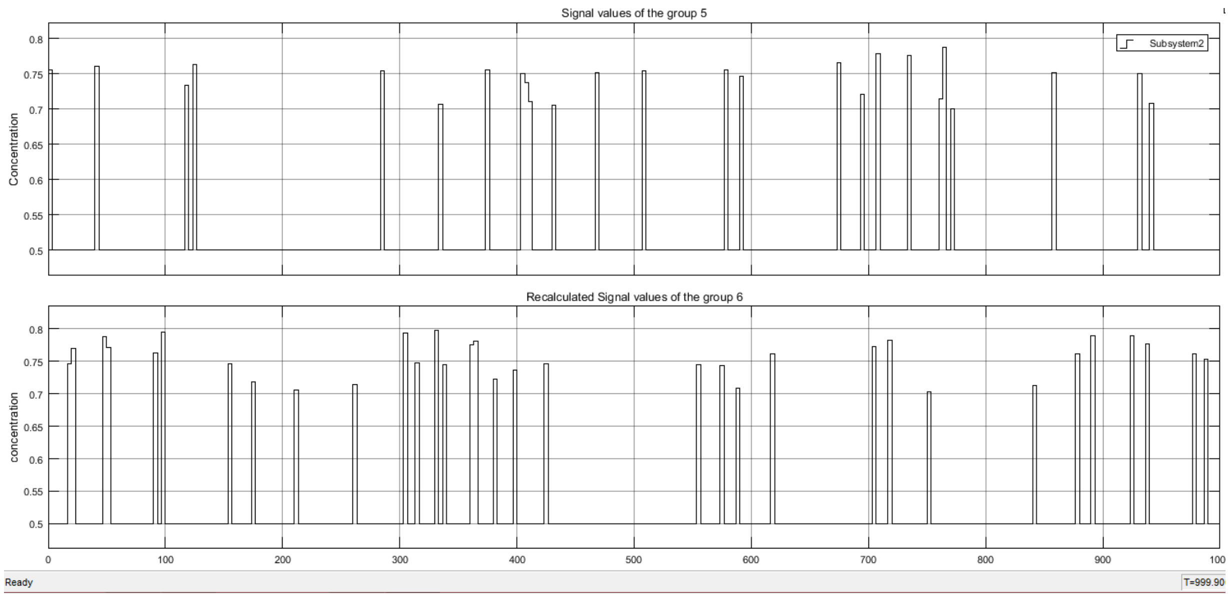

Figure 3-15: Signal of group 5 against the recalculated values of signal 6

2. The aim of the above transfer of the signal values was to find the best possible fit of the two diagrams. If we find the maximum value of the cross-correlation function of the two diagrams together with the related lag, the latter is the required delay to be given to the other diagram. Therefore a simple code for each combination is written in MATLAB to find the lag. For instance, the MATLAB Code below is related to the above combination of the groups 5 and 6

```
[cross_corr3 lags3]=xcorr(s5,s6)
b3=[cross_corr3 lags3'];
c3=max(b3(:,1));
d3=find(b3(:,1)==c3);
delay_3=b3(d3,2)
t=[0:3.333:1000]';
S5=[t,s5];
S6=[t,s6_1];.
```

Finally, now that all the required variables are provided, the model of the active control over inflow could be analyzed. If the value of delay (lag) is positive, it means that delay should be given to the upper group. Otherwise, the absolute value of the delay should be given to the bottom group. The rest of the calculations of the averaging factor are the same as done in the previous section. The Figure 3-16 demonstrates the block diagram of the model for the experiment with 10 groups and the Table 5 represents the results of the three different experiments including 4, 8 and 10 groups.

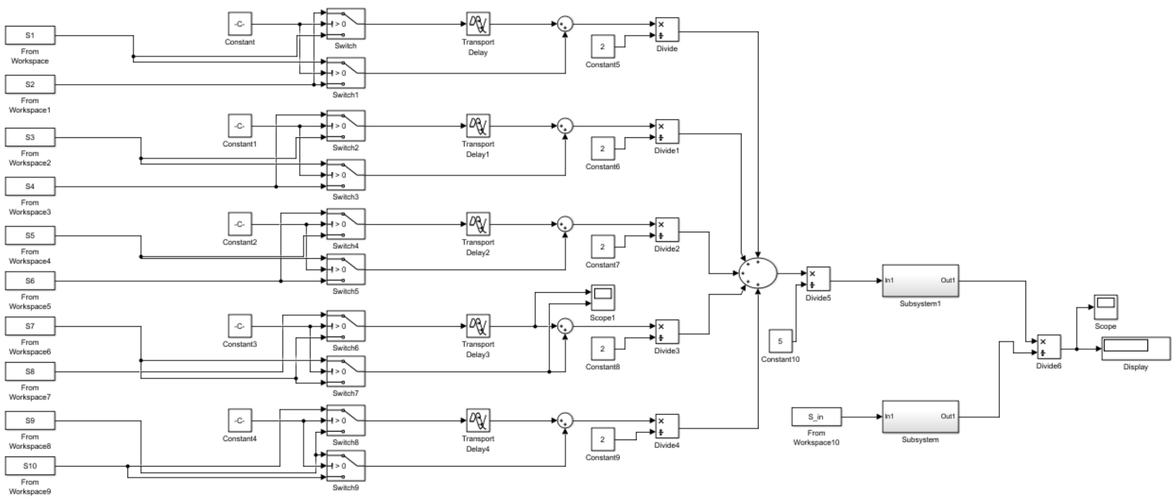

Figure 3-16: The model of the active control over the inflow

Table 3-3: Averaging factor for active control over inflow

Number of groups	**Averaging factor value**
4	0.111
8	0.022
10	0.01

As can be seen from the Table 5, the averaging factor value falls down by increasing the number of groups and division. It means that if one requires more accuracy and less deviation in outflow concentration, more divisions (less range value) are needed.

The interesting point to consider about the stochastic signal in the models that used for simulation is that the random source in Simulink used to produce uniform random numbers within the required range. However, the values are not absolutely non-correlated and stochastic over a short period and there is an autocorrelation in input signal (which was considered in equation 3-6 by as well). Therefore, choosing a random signal with normal distribution around the mean (Gaussian) should result in a less averaging factor value. Having repeated the passive control experiment with Gaussian random source, the observed values are shown in the Table 6.

Table 3-4: Passive control over the inflow by using Gaussian random source

number of pipes	**delay (h)**	**Time (h)**	**Experiment**					**Average (rounded)**
			1	**2**	**3**	**4**	**5**	
1	0	1000	1	1	1	1	1	1.0000
2	$3\frac{1}{3}$	1000	0.645	0.643	0.628	0.668	0.674	0.65
3	$6\frac{2}{3}$	1000	0.484	0.478	0.529	0.492	0.466	0.49
4	10	1000	0.412	0.361	0.408	0.388	0.394	0.39
5	$13\frac{1}{3}$	1000	0.224	0.262	0.24	0.215	0.197	0.23
6	$16\frac{2}{3}$	1000	0.169	0.215	0.178	0.191	0.176	0.19

3.3.2. Simultaneous dosing and mixing process with active control over inflow

The main idea of the simultaneous dosing and mixing process by active control over inflow is mixing time reduction, elimination of unnecessary components such as tank, impeller or motionless mixers or at least making improvements (optimization) to the system which in turn result in financial benefits. The shares of the materials in mixing process could be different (Yakovis & Chechurin, 2017). The equation 3-12 (Yakovis & Chechurin, 2017) shows the relation between the materials fractions in a mixing process:

$$u_1 + u_2 + \cdots + u_n = 1 \tag{3-12}$$

Where u_i shows the ratio of the material content to the sum of the materials to be mixed together. For simplification, in this study, the dosing process for two liquids (one of the liquids is water) will be analyzed. From the resource point of view, it is believed that the least changes with most efficient effect on the system should be investigated. Thus, it is not recommended to change the flow rate Q of the process due to client requirements or process standards. Similarly, changes in pressure (which can result in huge expenses of changes in pumps, operational costs or labor cost) should not be investigated.

Simulation

As mentioned before, for simplification, the idea is developed for blending two miscible liquids. The equation 3-13 shows the mass balance in the dilution or concentration process of a liquid in water:

$$u_1Q_1 + u_2Q_2 = Q_3 \tag{3-13}$$

The objective is to minimize the influence of the deviation in inflow concentration of the liquid. So, if the inflow concentration value gets over its nominal value (the liquid becomes more concentrated), the mixture should be diluted (adding more water and decreasing the share of the liquid). Conversely, if the concentration falls and comes below the nominal value, the share of the liquid should increase and less water should be added to the liquid. Below, the simple hydraulic block diagram of the abovementioned process is provided in the Figure 3-17. This model to be simulated, however, requires real fluid dynamics parameters such as fluid physical and chemical characteristics (for instance, viscosity and density), pipe geometric shape, roughness, laminar and turbulent flow margins and more specifications of the process, considering which are out of the scope of this project. The main interest in the above model is the function of the flow rate sensors, valves and their actuators (or pulse generators). Therefore, to make it simple, the model is projected in the Figure 3-18 and the hydraulic model of the system is not further developed in this study.

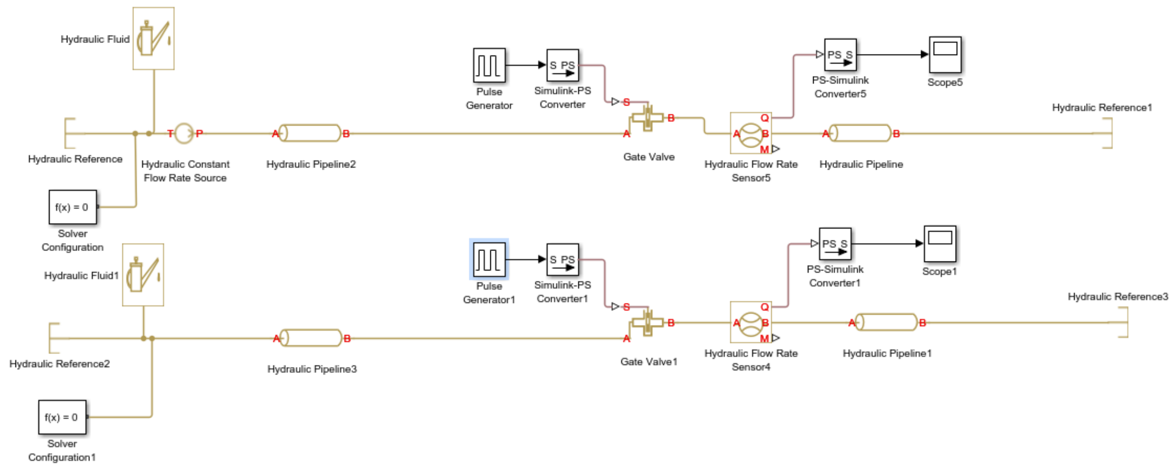

Figure 3-17: Hydraulic block diagram of the simultaneous dosing and mixing process

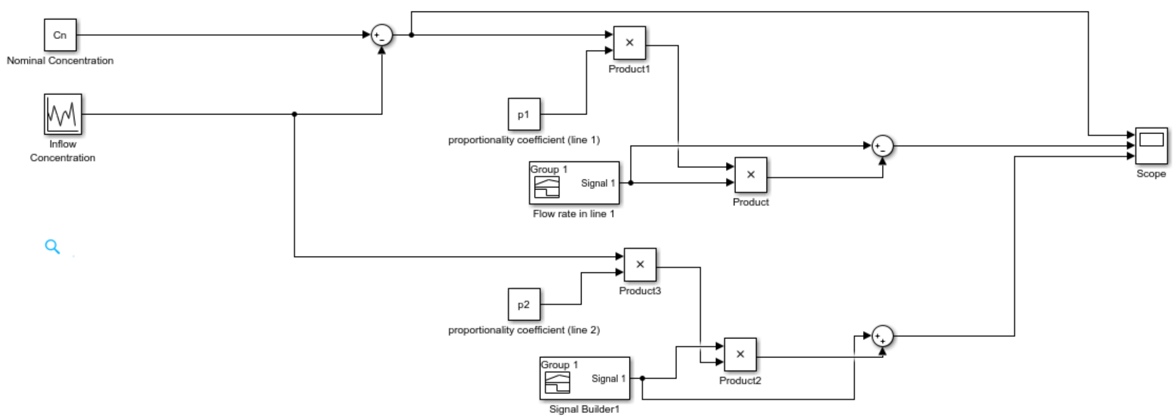

Figure 3-18: The correlation of the concentration sensor and the valves

This figure 3-18 represents the fact that by the increase of the concentration in liquid, the flow rate of the line 1 should decrease. P_1 is the proportionality coefficient that shows the ratio of change of the concentration in line 1 to the required change in flow rate line 1. Consequently, the flow control rate in the second line should change. P_2 is the proportionality coefficient of the ratio of change of the concentration in line 1 to change of the flow rate of water. This illustrates the dilution or concentrating process of the liquid. For example, fall of the concentration in the liquid results in the rise of flow rate 1 and consequently the drop of the flow rate 2 to make the liquid more concentrated. To give an illustration of how the simulation is fulfilled for the previous block diagram, let us assume that P_1 and P_2 are proportionality coefficients and 1% of increase in concentration results in 1% of decrease in flow rate 1 (P_1 =1) and 1% of increase in flow rate 2 (P_2 =1). The Figure 3-19 shows the change of the flow rates in lines 1 and 2 according to the change in liquid concentration.

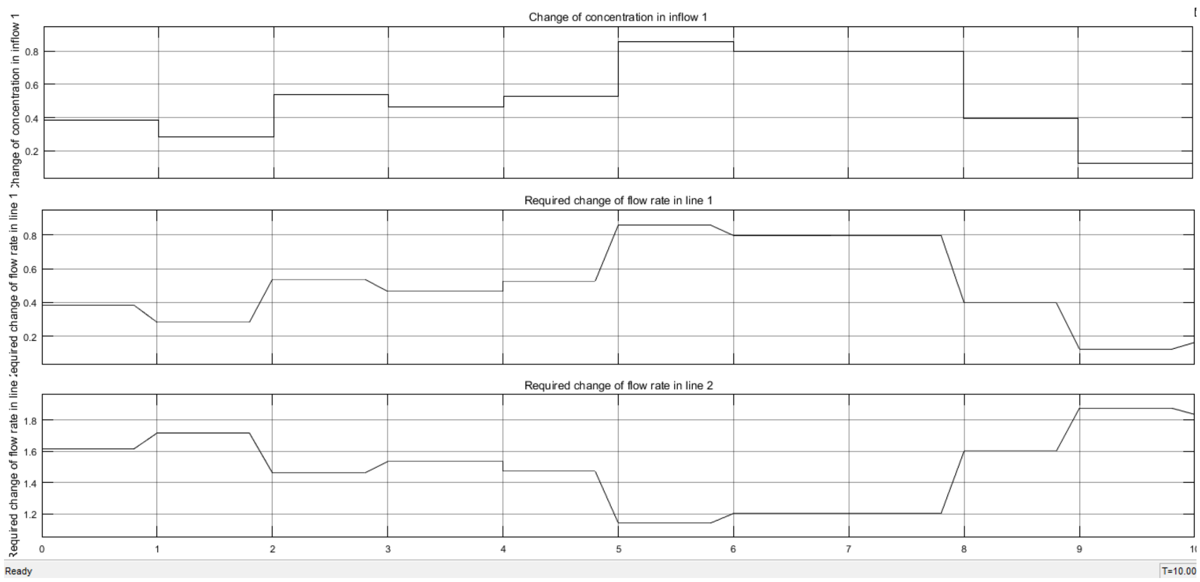

Figure 3-19: Changes of concentration in liquid 1 and flow rate of the lines 1 and 2

3.4. Summary of the simulations and results

At the first stage (mixing process by using an impeller) the mathematical model from previous study of Yakovis and Chechurin (2017) on mixing process was simulated by knowing the required averaging factor, mass of the mixture, nominal inflow concentration and the frequency of deviations in inflow. The mass was applied in the transfer function in Simulink. This was just to show how mixing process by knowing different parameters of the process can be simulated. No new idea was generated at this stage.

Next, the mathematical model from previous study of Yakovis and Chechurin (2017) on mixing process was simulated. The assumption was that by dividing the inflow into more portions and delaying the portions based on the intervals equal to the stochastic concentration change period, the averaging factor should improve (fall). The results of the simulations confirm the assumption.

At the third stage (active control over inflow), the assumption was that by smart division of the inflow to more portions, delaying one portion (the duration of delay is calculated by correlation function), combining the two portions after the delay and finally integrating the whole content of the mixture, the averaging factor of mixing should improve significantly. The results of the simulation confirms the assumption. In order to make the results more comprehensive, the Table 7 compares the results of the mixing process with and without impeller (passive and active control over inflow) by using both uniform and Gaussian random source to give a better view from the process.

Table 3-5: A comparison of the results of different mixing methods (Uniform and Gaussian)

Method	**Number of portions in passive control**	**Number of groups and combinations in active control**	**Uniform**	**Gaussian**
impeller	-	-	0.464	0.2
Passive control over inflow	1	-	1	1
	2	-	0.56	0.65
	3	-	0.38	0.49
	4	-	0.28	0.39
	5	-	0.21	0.23
	6	-	0.18	0.19
Active control over inflow	-	4 (2 combinations)	0.111	0.002
	-	8 (4 combinations)	0.022	0.0004
	-	10 (5 combinations)	0.010	0.002

At the final stage, the new technology of simultaneous mixing and dosing process was considered. The assumption was that by using a sensor for measuring concentration in the liquid line and two gate valves on both liquid and water lines for dilution or concentration process (where both gate valves receive continuous feed forward from the sensor of concentration), the mixture is self-averaged in the pipe. Therefore, the need for static mixer, tank and impeller is eliminated. The results of the simulation confirms the assumption.

Symbols

3.1

D Impeller diameter

H Liquid depth

N rotational speed of the impeller

Re Reynolds Number

T Tank diameter

t_m Mixing time

W Impeller width

μ Liquid viscosity

ρ Liquid density

3.2.1

C_{in} Range of deviation in inflow concentration (from zero to 1)

C_{req} The required nominal concentration in outflow

D_{in} Inflow concentration

D_{out} Outflow concentration

N Number of portions inflow divided into

P Mixing material mass

Q Mass flow rate

T Tank volume

ζ Frequency of change in inflow concentration

η Averaging factor

$G(t)$ The growth of the integral value

3.2.2.

u_i The share of the liquid (i) in the liquor

P_i Proportionality coefficient

4. DISCUSSION

The discussion chapter is divided into three separate subchapters. In the first subchapter, the practical implications of the results, including the technical conceptualization, technological application and a rough economic analysis of using the equipment are investigated. In the second subchapter, the main characteristics of the mathematical modelling as a systematic creativity technique are taken into account. The last subchapter is devoted to the possible strategies for popularization of mathematical modelling as a systematic creativity technique for radical innovation in Finland.

4.1. Practical implications

The practical implications of the empirical study in chemical mixing process is analyzed further in this subchapter. This subchapter, in turn is divided to technical conceptualization, technological applications and a rough economic analysis of using the equipment.

4.1.1. Technical conceptualization

Now that the ideas are introduced and the results from the simulations achieved, one may think about the technical aspects of the ideas, how to conceptualize them and screen the developed ideas. In this subchapter, conceptualization phase of systems engineering for the ideas developed in the previous chapter are analyzed briefly.

4.1.1.1. Technical solutions for passive and active control

The basic idea of passive control over inflow by delaying portions from Yakovis and Chechurin (2017) was simulated by Simulink and the results confirmed the decrease of averaging factor by increasing the number of portions that the inflow was divided into. Having developed the idea further using an active control over inflow and smart control over the process by combining the right portions together, the decrease of averaging factor was noticeable. The simulations mathematically confirmed the assumption that the more portions inflow is divided to (of course by having access to more accurate measuring instruments for concentration) the less would be the averaging factor.

However, the findings from the mathematical models and simulations do not guarantee that the models work in a chemical mixing process. Having discussed the physical solution with an expert in chemical process industry and a full professor in academia, it was found out that the physical solution for the model could not be considered persuasive for an active firm in chemical industry. The technical solution is neither technically nor economically considered convincing for many firms in chemical industries. They are not easily convinced for technology change unless a notable profitability from the change without losing the process quality is visible. If the inflow is divided to many portions, half of which should be delayed and sent to mixing pipe or tank later, these delays and reinjecting the liquids to the system (to be combined with another portions) require pumps that impose far more expenses to the process than a mechanical agitator with a mixing tank does. Storing the liquid in a cylinder and release by gravity force could also be an option to avoid using pumps. Yet, the threat of dead zones in the cylinders does not satisfy the process standards and neither this idea is considered further.

A creative idea is that delaying the liquid still can be considered by prolonging its route to the pipe or tank where mixing is performed, so the pressure does not drop significantly, the need for pump would be eliminated and the liquid circulation in pipes prevents creation of dead zones. This can be done by using, for instance, a spiral or helical shaped pipe, shown in Figure 4-1, in parallel with the portions that are not due to delay and are straight line pipes. The pipe length should, however, automatically be adjusted for each change in inflow concentration. This makes the realization of the idea quite complicated both material-wise (flexibility of the material could be in contradiction with process codes and standards) and from the perspective of manufacturing (the process automation according to the required adjustability of the pipe is quite complicated). Nevertheless, this idea could be considered for further development, but not as an option for this study. Another idea for this solution was to save the portions that should be delayed in a cylinder and add them after the required delay to the system vertically without a pump by exploiting from gravity force. The idea technically was rejected because of the dead zone in the cylinders. The technical implementation of the idea for passive and active control over inflow is not discussed further in this study.

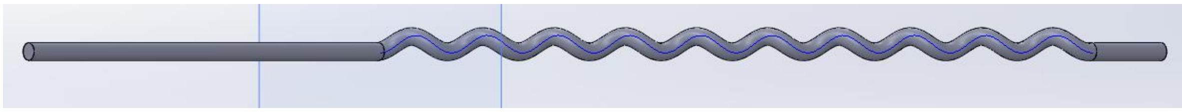

Figure 4-1: Helical shaped pipe for giving delay to portions

4.1.1.2. Technical solutions for simultaneous dosing and mixing

The realization of the idea can be done by installing a regulating valve (a gate valve for example) in each line and a sensor for measuring the concentration in the liquid of line 1 continuously, where the valves operate according to the feedback received from the sensor. As a quick tip to have an idea of what should be done to determine P_1 and P_2, let us consider the architecture of a simple gate valve (Mathworks, 2016) in the Figure 4-2, which consists of an orifice and a gate, movement of which is perpendicular to the axis of the orifice. The gate orifice size is the same as the orifice size on the housing and movement of the gate causes opening and closing the valve passage.

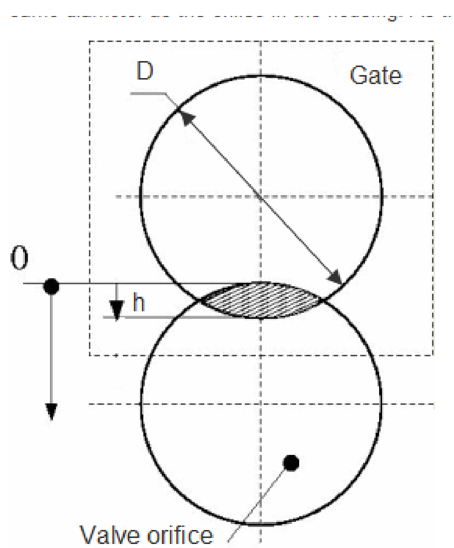

Figure 4-2: Simple gate valve architecture (source: Mathworks)

According to Mathworks (2016), the factors involved in considering the flow rate (Q) through the valve are the orifice diameter (D), instantaneous orifice passage area $A(h)$, pressure differential in two terminals of the valve (P), flow discharge coefficient (C), initial opening (X_0), Gate displacement (X), fluid density(ρ) and kinematic viscosity(v), critical Reynolds number(Re_{cr}), minimum pressure for turbulent flow (P_{cr}), valve instantaneous hydraulic diameter (D_h) and leakage area (A_{leak}).

For the simulation in Figure 24 where P_1=P_2=1, the initial opening position of the valves should be on 50% of the orifice area at the nominal concentration of the liquid. For instance, if the nominal concentration of the liquid is 15%, both valves should be adjusted semi-open at 50% of the orifice area for this concentration, in such a way that it would be possible to increase or decrease the flow rate according to the concentration change of the liquid. Then, the relation between 1% of increase in concentration of the liquid, 1% of closing the gate valve 1 (the orifice area to be covered by the gate 1) and 1% of opening the valve 2 (the orifice area to be uncovered by the gate 2) should be investigated by the abovementioned factors. Having said that, it could be possible that P_1 and P_2 will not be simply proportionality coefficients. In more complex situations, P_1 and P_2 could be linear or non-linear functions of the change of concentration. Nonlinear scaling factors (because of the complexity of the system) might affect the valve opening and closing process. The mechatronics control of valves and the sensor according to P_1 and P_2 are not of the interest of this study. For this case, simple linear operating valves are considered to simplify the task.

4.1.2. Technological implications

Now that the results from simulations of simultaneous dosing and mixing process achieved and a new idea developed from the initial process, let us assess the possible technological applications of the product. Although the idea is very simple and regards blending of two miscible liquids (particularly considered for dilution and concentrating of one liquid by solving in water) which covers a small fraction of mixing processes in chemical industries, it can still have various applications, especially when accuracy is not the case. In some industries, precise dosing is critical and instrumentation that is more explicit is required such as in pharmaceutical, agriculture, water treatment and other industries. In these cases, energy costs is not the most important factor and accuracy is essential for the business. Needless to say is that further development of the idea might have a significant contribution to mixing process by covering more and more processes. As it pertains to blending of two miscible liquids, the device could be applied for concentration averaging and liquor dosing/metering in both off line and pipeline mixing. It should be borne in mind that homogenization of the liquids is different from the concentration of the mixture. Accordingly, the following benefits in the applications for the equipment could be analyzed:

4.1.2.1. Concentration averaging

In this study, the deviation of inflow concentration was the main variable and the device can act as a catalyst for decreasing the mixing time (when reaching the required concentration in outflow is the main objective of mixing process) or eliminating the mixing equipment. Depending on the process requirements and time restrictions, the tank could be eliminated and instead a static mixer together with the equipment performs the mixing process and the process time can decrease.

The interesting point of this application of the equipment is that when a change in the outflow concentration by holding the volumetric/mass flow rate constant is required (for instance due to new requirements of clients or process change), there would be no need to change the inlet pressure of the liquid. For example, if the concentration of a certain type of an Acid should increase from 20% to 30% (by maintaining the volumetric flow rate constant), there is no need to change the inlet pressure of the Acid to increase the concentration. This can be done by partially opening the valve of the Acid line, closing the solvent or both actions at the same time. Thus, further operating costs for pressure change can be avoided. The Figure 4-3 is a simple representation of the equipment deployment in blending two miscible liquids.

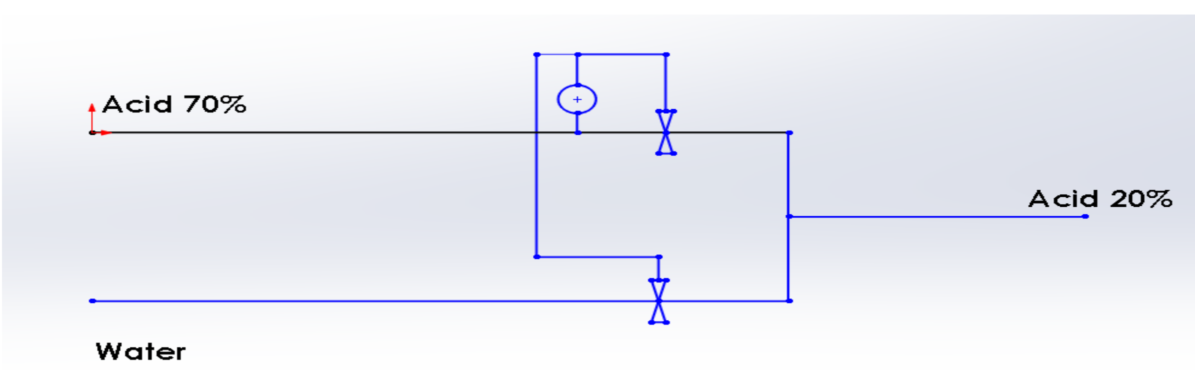

Figure 4-3: Equipment deployment in blending two miscible liquids

4.1.2.2. Offline mixing applications

The followings are the benefits achieved through the application of the equipment in offline mixing process:

- If homogenization requires mechanical agitation (for example because of the high difference in liquids viscosity or due to mixing time restrictions), the equipment reduces mixing time. If there is no restriction for mixing time or the prolongation of mixing time does not affect the whole process of the firm, then mechanical agitation could be even eliminated or replaced by agitators consuming less energy.
- If the homogenization process does not require any mechanical agitation and liquids are blended easily, an accurate dosing by the equipment before blending reduces the mixing process time even more.

4.1.2.3. In-line mixing applications

The followings are the benefits achieved through the application of the equipment in inline mixing process:

- Dosing pumps can be replaced by the equipment and a cheaper pump providing the required inlet pressure for less accurate processes. This is possible only after the pump time lag for the certain pressure. This, in turn, reduces capital and operating costs. The change in dosing and mixing time (increase or decrease) requires more experiments and observations which is out-scoped.
- Depending on the flow regime (laminar or turbulent) and time restrictions for the process, the need for using static or dynamic (rotor stator) mixers could be omitted or discolored by less costly mixers.

All in all, without considering the required observations for finding out more advantages, the equipment will at least reduce mixing time in concentration averaging, off line and pipeline mixing, which in fact results in an increase in revenue and profit margin. Furthermore, the device can mitigate the impacts of unexpected drop or excess of the required pressure by keeping the flow rate constant at the required level. It can also remove the need for expensive metering pumps by being replaced in the process together with a far less costly pump that provides the required pressure for the needed flow rate (the piping system and pipe diameter assumed to be the same).

4.1.3. Economic analysis

The next step after presenting technological applications of the equipment is to understand how it is profitable for a business and whether it is worth going for the technology or not. Of course, profitability analysis is not sufficient for a project manager to decide whether the device is the right technology for the firm or not. The equipment replacement process is not an objective decision made only by quantitative analysis. The CEO or any project manager who is involved in making the replacement decision might have different criteria and policies. Many more analysis such as customer satisfaction, market research, risk analysis and resource prediction are required for making the right decision. However, it is still essential to have an overview of the selection by doing a profitability analysis. This is an initial step for many investors in any field. First, let us see who the stakeholders of the device are. The device is dealt in B2B businesses rather than in B2C, because the function is industrial mixing. Of course, for small scale projects the device can also be considered for B2C projects, but the focus is in B2B businesses. Thus, one should think about the possible suppliers for the device who mass-produces the product and the clients in chemical industry and process plants. Depending on whether the product is aimed to be used for a new process plant (either an active firm or a prospective entrepreneur who is planning to commission a process plant) or an active plant, the decision made could be different. In the former case, the decision is made easier, because there is no investigation and analysis for the current products used for mixing and dosing. In the latter though, the analysis require more careful consideration.

As mentioned before, decision-making process depends on many factors that should be taken into account by project managers. Let us assume that that the product has already been prototyped and the project manager has access to the specification of the new equipment in addition to the one currently is in use. According to the application of the product, there could be different combinations of the equipment with pumps or static mixers and tanks. These should be seen in the analysis of replacement for any process. For instance, the type of combination in a simple dilution process is different from the homogenization of two liquid of high viscosity.

The author aimed to find an algorithm for making profitability analysis easier and choosing between the two equipment more confidently in this project. One should notice that equipment in this context means the combination of the products used for performing the required function (which could be mixing of two miscible liquids, dosing them or a combination of both). This analysis in turn gives the project manager a proper tool for the better selection of the required equipment. The main papers used for preparing this algorithm are the studies by Kusaka and Suzuki (1990) and (M.Fraser & M.Jewkes, 2013). After completing the model, the comparison is made in the context of chemical mixing and dosing processes.

4.1.3.1. Comparison of two mutually excluded technology

The comparison is made between two technologies where both fulfill the same function, yet the equipment characteristics, initial costs, operating costs and other specifications are different. The equipment 1 is the same model of the current equipment (brand new) and the equipment 2 is a recently-developed technology. For simplification at the first stage, the following lemmas hold. Note that these lemmas are not true in reality and will be reconsidered later in this subchapter for more precise analysis.

Lemma 1: The product from both technologies are quite the same.

Lemma 2: Both technologies have got the same economic life and both are adaptable to client requirements at the same level.

Lemma 3: The amount of outflow per year is constant. The operating costs and efficiency functions are constant over time in both equipment. That is to say, the first derivative of the functions are zero and depreciation is neglected. Also, the labor cost is constant over the project life.

Lemma 4: The interest rate (r) during the economic life of the equipment and the inflation rate do not change.

Lemma 5: The production volume is at the saturation level and the equipment works 24/7 in three shifts. Thus, inflows and profits from both equipment are constant over time and profits could be considered as annuities for this problem. The salvage value of the equipment is evenly divided into the number of years of equipment service life and is added to the amount of annuity.

The subscript (i) refers to the equipment in the parameter given below and the subscript (j) is a time indicator. (j) can be interpreted also as a non-integer value, since the time is a continuous variable. It is usually interpreted as an integer for cost-benefit analysis, unless the payback period calculation is of an interest.

Sal_o- Salvage value of the old equipment (Sal_o>=0)

C_i-Capital costs of equipment (i),

C_{ij}= f(purchase price (P_{ij}), training costs (T_{ij}), Installation costs (I_{ij}), Engineering costs (E_{ij}), Programming costs (Pr_{ij}), time[1])

$$C_{\mathrm{ij}} = P_{\mathrm{ij}} + T_{\mathrm{ij}} + I_{\mathrm{ij}} + E_{\mathrm{ij}} + Pr_{\mathrm{ij}} \tag{4-1}$$

O_{ij}-Operating costs of equipment *i* over time *j*

UEL_i- Useful Economic Life of equipment *i*

E_{ij}-Efficiency of equipment *i* over time *j*

OV_{ij}- Overhead costs of equipment *i* over time *j*

OV_{ij}=f(rental for office (Re_{ij}), utilities (U_{ij}), labor costs(L_{ij}), maintenance (M_{ij}), insurance (In_{ij}), tax, others)

$$OV_{\mathrm{ij}} = Re_{\mathrm{ij}} + U_{\mathrm{ij}} + L_{\mathrm{ij}} + M_{\mathrm{ij}} + In_{\mathrm{ij}} \tag{4-2}$$

S_{ij}- Safety costs of equipment *i* over time *j*

A_i-Adaptability of equipment *i* to client requirements

Sal_{ij}-Salvage value of equipment *i* in time *j* (could be zero or higher)

V_{ij}-Volume of production of equipment *i* over time *j*, in this case this volume itself is a function of the process time, because the working shifts are the same.

SP_{ij}-Sales price per volume

$Sales_{ij}$-Sales from equipment *i* over time *j*

$Sales_{ij}$=f(V_{ij}, SP_{ij})

$$Sales_{\mathrm{ij}} = V_{\mathrm{ij}}.SP_{\mathrm{ij}} \tag{4-3}$$

DTO_{ij}-Direct Total Operating costs of equipment *i* over time *j*

DTO_{ij}=f(O_{ij}, OV_{ij}, S_{ij})

$$DTO_{\mathrm{ij}} = O_{\mathrm{ij}} + OV_{\mathrm{ij}} + S_{\mathrm{ij}} \tag{4-4}$$

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[1] The capital costs of a new equipment change over time, meaning that the decision to buy the equipment one year later rather than today affects the capital costs.

IDTC-Indirect Total Operating Costs of equipment *i* over time *j*

IDTC=f(UEL_{ij}, E_{ij}, A_i)

As can be seen, operating costs, overhead costs, salvage value of the equipment after its service life and process time are the major variables that influence the calculations. This is of course, when assuming that lemmas 1-5 hold.

Now, one can easily compare the investments by the famous investment appraisal methods by considering constant outflows and annuities each year.

An_i- Equal annuity (annual savings) received by using equipment *i* in one period (one year)

$$An_{\mathrm{i}} = \ Sales_{\mathrm{i1}} + (Sal_{\mathrm{ij}}/j) - DTO_{\mathrm{i1}} - IDTO_{\mathrm{i1}} \tag{4-5}$$

The minimum required annuity per year can be figured out by using capital recovery formula. Please note that annuities (including the savage value of the equipment) are the means of compensating the capital investment. Therefore:

$$An_{\mathrm{min}} = (C_{\mathrm{ij}} - Sal_{\mathrm{ij}}) * ((1+r)^j - 1)/(i * (1+r)^j) + Sal_{\mathrm{ij}} * i \tag{4-6}$$

Present Value (Present Worth)

The equation 4-7 is used for calculating Net Present Value (NPV). The higher the NPV, the more profitable is the project (for the same project lifetime):

$$NPV = \sum_{t=0}^{T} \frac{An_i}{(1+r)^t} - C_i + Sal_o \tag{4-7}$$

PW_{1j}- Present Worth of cash flows generated by equipment 1 in time *j*

$$PW_{1\mathrm{j}} = (An_1/((1+r)^j - 1)/(i * (1+r)^j) - C_1 + Sal_{\mathrm{o}} \tag{4-8}$$

PW_{2j}-Present Worth of cash flows generated by equipment 2 in time *j*

$$PW_{2\mathrm{j}} = (An_2/((1+r)^j - 1)/(i * (1+r)^j) - C_2 + Sal_{\mathrm{o}} \tag{4-9}$$

If PW_{2j}>PW_{1j}, then purchasing equipment 2 instead of equipment 1 is the better choice.

Internal Rate of Return (IRR)

The equation 4-10is used for calculating the internal rate of return IRR (*i** is the IRR):

$$\sum_{t=0}^{T} R_t (1+i^*)^{-t} = \sum_{t=0}^{T} D_t (1+i^*)^{-t} \tag{4-10}$$

Or,

$$\sum_{t=0}^{T} (C_{ij} - Sal_o)(1+i_i^*)^{-t} = \sum_{t=0}^{T} (R_{\mathrm{ij}} + Sal_{\mathrm{ij}} - DTO_{\mathrm{ij}} - IDTO_{\mathrm{ij}})(1+i_i^*)^{-t} \tag{4-11}$$

By replacing the present values of the parameters in the equation 26, the IRR is easily figured out. The higher IRR illustrates the riskier and worse option for selecting.

Discounted Payback Period

Payback Period is the time that the initial costs of the project would be covered. However, for a more realistic vision, Discounted Payback Period is the right parameter to choose. This indicator is one of the most important ones for investors, since they must know when their money is back. Thus, cumulative Discounted Cash Flows (DCF) should be subtracted from the initial investments over time. The year that negative difference turns to positive cash flow is the year of payback. To precisely calculate the discounted payback period, equation 4-12 is used.

Table 4-1: Discounted Payback Period calculation

Year	Cash Flow	Interest Rate	Discounted Cash Flow	Cumulative Discounted Cash Flow
0	$-C_i$	r%	$-C_i$	$-C_i$
1	An_i	r%	$An_i(1+r)$	$-C_i+$ $An_i(1+r)$
2	An_i	r%	$An_i(1+r)^2$	$-C_i+$ $An_i(1+r)^2$
...	An_i	r%	…	…
n-1	An_i	r%	$An_i(1+r)^{(n-1)}$	Negative value (X_1)
n	An_i	r%	$An_i(1+r)^n$	Positive value (X_2)

$$Discounted\ Payback\ Period = (n+1) + \frac{\mathrm{abs}(X_1)}{An_i(1+r)^n} \quad (4\text{-}12)$$

4.1.3.2. Comparison of equipment in mixing project

Having modeled the economic calculation of the equipment replacement case, the case study of chemical mixing process can be projected in the model to find out the better choice from the economic point of view. The equipment 1 was the brand new of the same equipment in use and the equipment 2 is the new equipment developed in this study for simultaneous dosing and mixing process. The comparison is quite rough at this point apparently, because the design was not completed technically and prototyping was out-scoped. The Table 9 demonstrates the comparison of the parameters between two equipment. The better choice considering each equipment marked by an X sign. This is the point of time where the unrealistic lemmas 1-5 should change to the right ones and the influence could be seen in the big picture of the comparison. Obviously, despite not having access to all the required data, one ends up in that the developed equipment by the university is the better choice from the economic point of view.

Table 4-2: Comparison of technical parameters between equipment 1 and 2

Type of costs	**Detailed costs**	**Equipment 1**	**Equipment 2**
Capital Investment costs	Purchase cost		X
	Training cost	X	
	Installation cost	not known yet	
	Engineering cost		X
	Programming cost	not known yet	
	Adaptability	not known yet	
	Service life		X
	Efficiency		X
Overhead costs	Rental of office		X
	Utility		X

	Maintenance		X
	Insurance		X
	Labor		X
	Tax		X
	Safety costs		X
	Operating cost		X
	Rate of Salvage value to capital investment		X
Sales	Process time		X
	Production volume		X

This information can be used now for the investment appraisal methods and the important indicators of profitability analysis could be roughly compared in two equipment. Equipment 2 causes less costs and brings more profits in comparison with the equipment 1. The Table 10 is a brief comparison of the profitability analysis indicators in two equipment.

Table 4-3: Profitability analysis indicators for equipment 1 and 2

Method	**Equipment 1**	**Equipment 2**
Net Present Value	Lower	Higher
IRR	Higher	Lower
Discounted Payback Period	Longer	Shorter

4.2. Main characteristics of the mathematical modelling as a systematic creativity technique in mixing process

To be able to answer to the RQ1, the findings of the empirical study is compared with the literature and the new concepts are described as the characteristics of the mathematical modelling where it is used purposefully as a systematic creativity technique.

There are similarities and differences between the mathematical modelling approach towards creativity in the empirical study and the creativity process model HPG (Ogot & Okudan, 2006). Looking at the structure of the empirical part of the study, it is understood that the process started by careful investigation and study of the area of research and getting to know to the main concepts of mixing and dosing processes. Then, the problems geared towards mixing process were recognized and formulated in a precise form. Subsequently, preliminary solutions to the problem were suggested by simulation of the passive control over inflow. Then the project progress slowed down before coming up with the idea of active control over inflow and decelerated even more while transitioning to the simultaneous mixing and dosing process idea. The later idea was selected for evaluation and conceptualization started. Finally, after interviews and financial analysis, the idea was accepted for being prototyped in order to have better understanding of the product weaknesses and market interest for the product. The structure of the empirical part resembles the creativity process model HPG. It starts by careful study of mixing and dosing process and coming up with preliminary solutions (first insight and partly saturation), then after the successful simulation of the passive control over inflow the saturation phase completed and incubation phase started, when no useful idea generated. Illumination started by the idea of active control over inflow and stopped by completing it. Because the idea was not ready for being presented technologically, the iteration process from illumination to incubation phase repeated several times until the last idea of simultaneous mixing and dosing shaped. Thus, this study confirms the creativity process model HPG empirically.

Nevertheless, there is a big difference in the systematic creativity where mathematical modelling was the technique to find a solution for mixing process in comparison with other techniques. Regardless of whether there is an iteration from illumination to incubation, the creativity and efforts to find a solution did not stop. The author continuously tried different methods and ways to reach the final solution. This is similar, for instance, in TRIZ and the efforts to end up in an acceptable solution are continuous, but with more emphasis when it comes to mathematical modelling. That is to say, the incubation phase in mathematical modelling approach towards creativity is more dynamic and less confusing. Furthermore, the transitioning process from incubation to illumination stage in mathematical modelling of the mixing process is not as accidental as it is in HPG model. For instance, the main idea of active control and passive control over inflow (in terms of division and delay) resemble. Similarly, the major idea of averaging in simultaneous mixing and dosing looks like the idea of combing the two parts of different concentrations in active control over inflow are the same, hence more consistency can be seen from the entire approach and the result. The Figure 4-4 compares the mathematical modelling approach towards creativity with the HPG creativity process model.

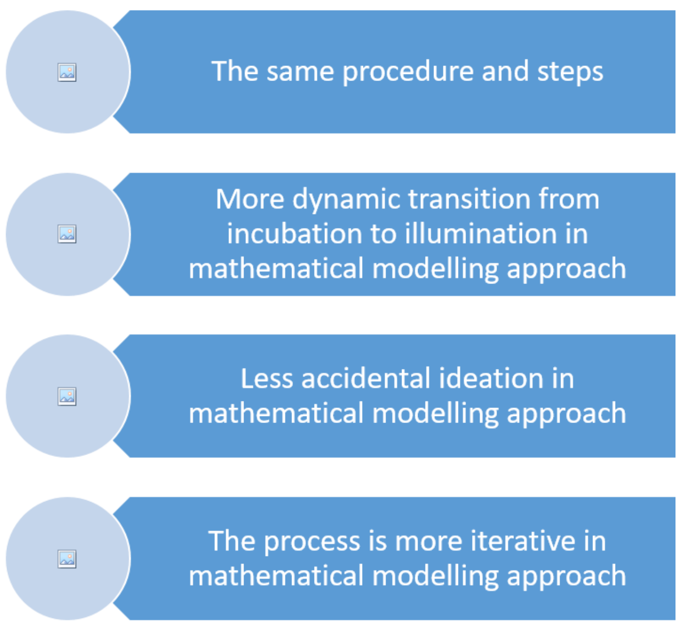

Figure 4-4: Mathematical modelling approach towards creativity vs. HPG model

This study implies to perhaps an overlooked characteristic of the product and process simulation. One of the characteristics of the mathematical modelling that helps dramatically in ideation phase is the ability to simulate. This, not only immediately gives a hint to the correctness and accuracy of the trial and effort method and possible iterations, but it also provides a visual environment for the designer which in turn results in better and faster creativity of the designer (Gaubinger, et al., 2015). By putting different items and mathematical operations together in Simulink or other simulation software, one thinks more effectively about the functionality of the system components and is likely to make radical changes by changing the components or their attributions with the least possible resources.

The iteration process in mathematical modelling should be highlighted. The iteration process from illumination to incubation was quite time-consuming all over the ideation phase for mixing process. Nonetheless, this could not be perceived as a downside of mathematical modelling as an approach towards systematic creativity. The iteration process makes the approach and thus the results more consistent. This is very similar when it comes to, for example, Scrum methodology for product development. Therefore, the people who devote their time for New Product Development, particularly by mathematical modelling, should be patient enough and have soaring level of stamina.

The outcome of the ideation phase by mathematical modelling approach could be very different from the start point or even be deployed in other industries. For instance, in the approach towards mixing and dosing processes by mathematical modelling, the analysis started by the mixing process in general, but finished by a simple product which can be applied for mixing and dosing of two miscible liquids. It should be born in mind that this interpretation could be biased, because this can be also the result of the lack of expertise of the author in complicated process engineering issues. The author tried to simplify the modelling and problem as much as possible to be able to come up with an outcome. If he had sufficient knowledge in process engineering, he would have been likely to end up in different or perhaps better results. Thus, this characteristic of the mathematical modelling approach towards systematic creativity cannot be generalized. Nevertheless, it is confirmed that one may end up in an outcome different from the beginning point.

Simplification of the problems and controlling the independent variables (where there is no correlation between two variables) could help to discover more and more ideas. In the empirical part, the main variable was the stochastic deviation in concentration and viscosity of the liquid, density, fluid dynamic parameters and other variables that were related to the liquid homogenization were controlled to simplify the problem of averaging. Thus, even experts in certain fields can simplify the problems in order to achieve more and more results and ideas. The usefulness of the ideas is not the issue at the ideation stage as mentioned before.

One of the drawbacks of the application of mathematical modelling for creativity purpose is that the ideas generated and theoretically accepted might not be technically or economically feasible. For instance, regarding the active control over inflow, the horizontal and parallel piping while delaying the portions require additional pumps which are not economically feasible. On the other hand, the vertical and parallel piping by delaying the portions using vertical cylinders result in dead zones which prevents the further development of the idea technically. Thus, before any prototyping after an approved mathematical model approach, sharing the idea with experts in the field is essential. The Figure 4-5 demonstrates characteristics of mathematical modelling to be used for as a systematic creativity technique.

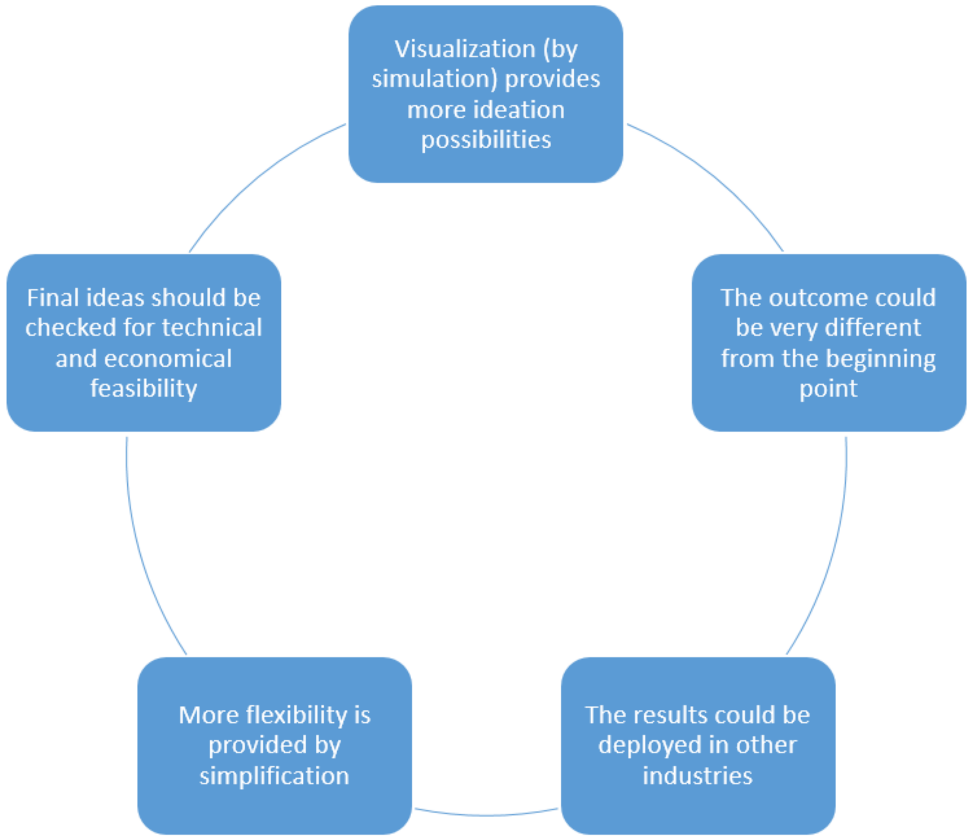

Figure 4-5: Characteristics of mathematical modelling as a systematic creativity technique

4.3. Possible strategies to increase the popularity of mathematical modelling as a systematic creativity technique in Finnish society

The profitability analysis conducted for the equipment replacement of the case study was based on the lemma that interest rate and inflation are constant over the economic life of the project. In fact, this is not realistic in many countries of the world, where political conditions, international relations, economic situations and many more factors are due to drastic changes and is unstable. Finland on the other hand is one of the countries that experienced less change in interest rate and inflation over time and its economy is known to be more stable in comparison with many other countries. Furthermore, the workplace innovation factor and employee satisfaction in Finland is quite high (Lorenz, 2015). These factors make Finland an ideal country for innovative activities. It is of interest to understand what should be done in Finland and

Finnish society to make systematic creativity (mathematical modelling in particular) more popular. That is to find out the necessary actions in all layers of Finnish society including individuals, organizations, universities and the government.

Although Finland is well-known for its innovativeness, the statistics show that this is not the case in all innovation factors. Based on Bloomberg's reports (Bloomberg, 2015; Bloomberg, 2016), the input factors of tertiary efficiency and R&D intensity are quite high worldwide and the first in European Union in 2014 and 2015. Yet, the output factors including high-tech, manufacturing and productivity are not amon the top countries in the world over the same period. There is a good progress, however, in 2016 and the indices show better results, not satisfactory yet though (Bloomberg, 2017). This fact shows that there still exist unsuccessful strategies towards innovation in the country.

A previous study conducted by the author of the thesis (Khademi, et al., 2017) shows that the application of systematic creativity (TRIZ in particular) in Finland is not that popular. It was understood that most of the companies had not even heard about it or if they had, they might had been resisting accepting it. The results showed an increase in idea generation, higher creativity in staff, better systematic thinking and teamwork, and higher work satisfaction where systematic creativity workshops conducted. Indeed, if companies had understood the value of systematic creativity, the productivity of individuals, organization performance and, consequently the GDP of Finland would have significantly increased.

The most important challenges found in Finnish companies for applying systematic creativity in their activities were the lack of motivation in employees and managers, being frustrated by unsuccessful attempts of prior workshops, risk of information leakage, lack of the required basic skills for systematic creativity workshops in employees, and the wrong management assumption on the systematic creativity approach towards innovation in industry or even in Finland. These were obvious challenges that could be seen in all companies investigated (Khademi, et al., 2017).

The Figure 4-6 demonstrates a simple overview of the innovation system in Finland, where the relationship between the elements of the system are demonstrated. The model has similarities with the innovation model of *Triple Helix*, developed by Etzkowitz and Leydesdorff (1996) where the government, industry and university are the core players of innovation in a country. The difference is that individuals are also considered in this model and government's policies are the base for other players' activities. The model also resembles the one presented by Boly, et al. (2014) in its top-down approach. However, that model has the focus on firm innovation. In this model the concentration is on the big picture of innovation system in Finland.

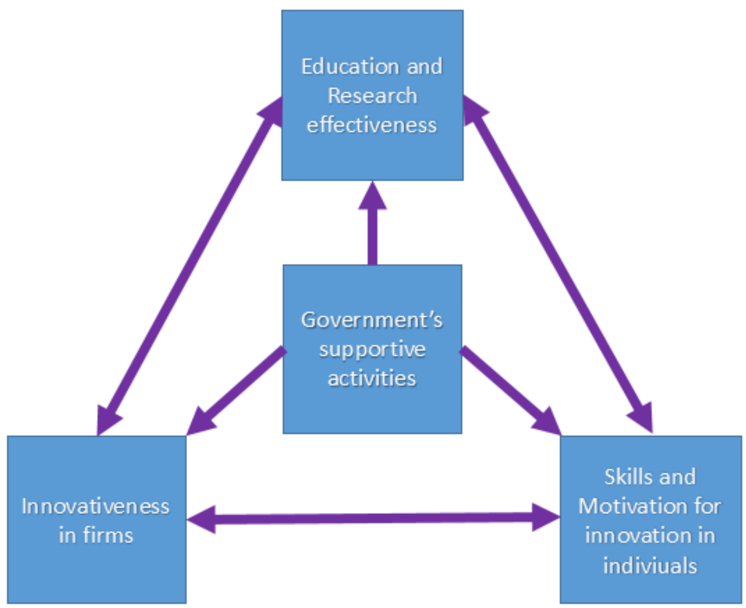

Figure 4-6:Innovation system in Finland (source: Khademi et al., 2016)

Finland, as mentioned before, has got one of the best education systems in the world (Bloomberg, 2016). There are, however criticisms that universities are not effective enough in order to contribute to national, regional and industrial innovation system (Montonen & Eriksson, 2013). A study by Montonen & Eriksson (2013) demonstrates that Finland needs far more work to do to teach innovation in schools and universities and innovation should be based more on practice rather than teaching theories. They also suggest that the 'innovation pratice' should be a continuous activity and it requires feedback from all the parties such as students, teachers and involved organizations. The continuity of innovation process has been emphasized not only in education, but also in organizations and companies, for instance in Bayhan, et al. (2013) and Humphreys, et al. (2005) studies. After the division of the higher education system into universities and *Polytechnics* (also called Universities of Applied Science), enrollment for engineering and science and consequently attention to math's and natural sciences in schools increased and Finland is among the top countries in these fields (Woiceshyn & Eriksson, 2014). On the other hand, a report from OECD (2010) about Finnish innovation system, indicated that Finnish government were considering a jump to non-technical business areas and currently there is an emphasis on business fields such as social welfare (Woiceshyn & Eriksson, 2014). This contradiction in strategic decision-making may have had detrimental effects on business atmosphere and employment rate in Finland.

Studying in Finnish universities has its own privileges for students. For instance, they usually write their paid theses in collaboration with the Finnish industry (Woiceshyn & Eriksson, 2014). This strong tie is beneficial for them in gaining a unique experience before entering the labor market and provides a good opportunity in finding the right network for their future career. Another endowment of the Finnish society for individuals to push the frontiers is the high level of trust in Finnish society that results in broader networks and collaborations (Woiceshyn & Eriksson, 2014; Kalmi & Kauhanen, 2008). It seems that Finnish society, schools, universities and companies provide an appropriate atmosphere for individuals to contribute to innovation in different levels of the country. Especially, individual's motivation in being innovative seems to be high. There is also a downside about the Finnish education system. The previous research by the author proves that systematic creativity techniques such as TRIZ is a missing course in master's degree programmes in Finnish universities (Khademi, et al., 2017). Similarly, mathematical modelling as a technique for radical innovation should be included in master's degree curricular and universities should allocate more courses related to innovation management. Universities might need more budget for innovation-related courses, but it seems to be a necessary step forward, because the output indicators of innovation in Finland are very low. The idea of including systematic creativity techniques in master's degree programmes leads to the elimination of the need for seminars and workshops at basic level in future or to minimize the required time and resources for training. This training would be very sensitive and skilled trainers are required for this purpose, because if the primary training course is not interesting, then the subsequent trials could be of no value.

Workplace innovation has become an attractive issue, especially in Europe since the start of the third millennium (Lorenz, 2015). Lorenz (2015) believes that organizational innovation by national level policies in Nordic countries has been successful in terms of workplace innovation such as VC (Value Creation) programme in Norway, TEKES in Finland and VINNOVA in Sweden. A comprehensive quantitative research conducted in Finland by Kalmi & Kauhanen (2008) that was based on some former studies outcomes has got the following outcomes: First, difference in workplace innovations such as information sharing, self-managed teams and training result in positive outcomes for employees such as better job influence, higher salaries, risen job satisfaction. Training itself influences on increased job security and higher job intensity. Second, workplace innovation has got positive implication on employee performance and innovativeness. Third, employee participation in decision-making, high level of trust in Finnish society and high job security level have positive outcomes for workplace innovation. Companies recruit employees that contribute to their level of innovativeness and competitiveness in the market (Haines-Gadd, 2015). In order to be innovative, employees should be both motivated and skilled in thinking and creativity and also be able to realize their ideas (Haines-Gadd, 2015). As mentioned before, one of the main dimensions of being innovative for employees is to provide an appropriate and continuous trend of training in the organizations.

The previous research by the author (Khademi, et al., 2017) also shows that Finnish companies complained about the lack of budget for workshops. On the other hand, it was understood that companies were willing to develop the ideas internally because of the risk of information leakage, but they all need the basic principles to ignite the procedure. One solution would be regular systematic creativity seminars supported by the key players of the innovation system in Finland, where companies can participate and get to know to the techniques first, and then further develop them by consultants in their companies for their own specific needs and finally deploy them regularly in their R&D departments. This could be also an approach for companies and individuals to make a wider network and possible joint projects in future.

Regardless of how useful it can be for a company in its application and outcomes, learning systematic creativity techniques is essential for individuals, because it improves the rate of idea generation, creativity in staff, systematic thinking, teamwork, and work satisfaction. These can increase the productivity of individuals, improve organization performance and, consequently, contribute to the growth of GDP in Finland significantly. The Figure 4-7 briefly shows the required strategies for increasing the popularity of Mathematical modelling as a systematic creativity technique in Finland.

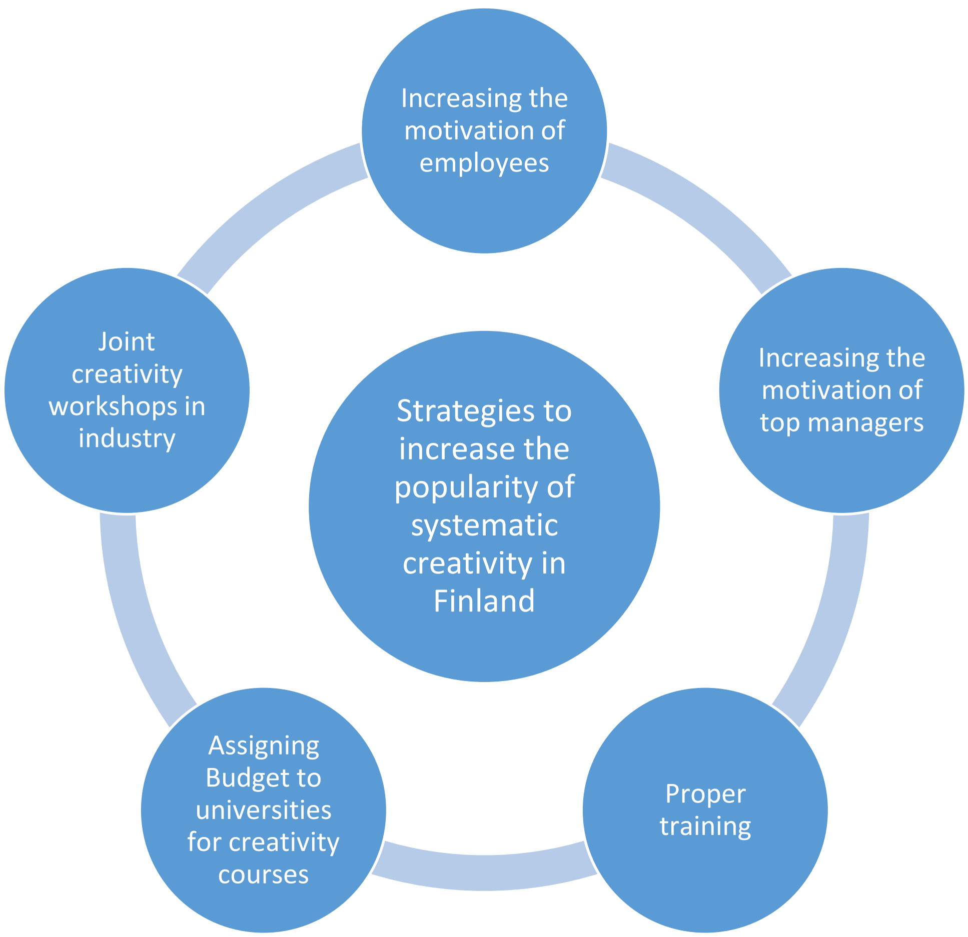

Figure 4-7: Strategies to increase the popularity of systematic creativity in Finland

Symbols

4.1.1.

$A(h)$ Instantaneous orifice passage area

A_{leak} Leakage area

C Flow discharge coefficient

D The orifice diameter

D_h Instantaneous hydraulic diameter

P Pressure differential in two terminals of the valve

P_{cr} Minimum pressure for turbulent flow valve

Q Flow rate through the valve

Re_{cr} Reynolds number

v Kinematic viscosity critical

X Gate displacement

X_0 Initial opening

ρ Fluid density

4.1.3

Sal_o Salvage value of the old equipment

C_i Capital costs of equipment *i*

O_{ij} Operating costs of equipment *i* over time *j*

UEL_i Useful Economic Life of equipment *i*

E_{ij} Efficiency of equipment *i* over time *j*

OV_{ij} Overhead costs of equipment *i* over time *j*

S_{ij} Safety costs of equipment *i* over time *j*

A_i Adaptability of equipment *i* to client requirements

Sal_{ij} Salvage value of equipment *i* in time *j* (could be zero or higher)

V_{ij} Volume of production of equipment *i* over time *j*

SP_{ij} Sales price per volume

$Sales_{ij}$ Sales from equipment *i* over time *j*

DTO_{ij} Direct Total Operating costs of equipment *i* over time *j*

IDTC Indirect Total Operating Costs of equipment *i* over time *j*

An_i Equal annuity (annual savings) received by using equipment i in one period

$An_{\min}$ Minimum required annuity

NPV Net Present Value

PW_{ij} Present worth of cash flows generated by equipment i in time j

IRR Internal Rate of Return

DCF Discounted Cash Flow

5. CONCLUSION

The focus of the study was discovering the role of mathematical modelling on radical innovation in chemical mixing process when it is used as a creativity technique. The literature lacks the material related to the objective. In order to answer the research question, simulations and interviews applied. The results show that mathematical modelling can be used as a systematic creativity technique for making radical innovations in chemical mixing industries. Technical conceptualization and technological implications of the ideation phase presented and the economic analysis for technology replacement confirmed the new technology. Similarities and differences between HPG creativity process model and mathematical modelling as a systematic creativity technique described. Characteristics of the mathematical modelling approach for radical innovation purpose in mixing process thoroughly explained. Finland was selected as a good alternative for feasibility analysis based on high innovation indicators and economic stability. Based on the prior research by the author of the thesis, the challenges of using systematic creativity techniques in Finland identified. Finally, possible strategies for increasing the popularity of systematic creativity (mathematical modelling technique for creativity in particular) presented.

5.1. Contribution to academia

The study contributes to academia by the empirical ideation in chemical mixing process by means of mathematical modelling. The case study chosen for examining the role of purposeful use of mathematical modelling for radical innovation was specific in chemical mixing process. Since countless events and physical rules can be described by differential equations, the chance of success for using the same approach for many technical and humanity-related problems is rather high. Having said that, the evidence to generalize the result to other industries is not sufficient yet.

5.2. Managerial implications

One of the most important messages the thesis has got for organizations is the possibility of widening the range of activities in R&D departments by adding the special group for mathematical modelling. This should not be confused with the activities where mathematical modelling is a part of a task for making optimization to the system, however. The particular R&D mathematical modelling group's activity would be modelling the problems they find in their organization regardless of the type of the problems. They can be related to a very specific issue in mechanical or electrical engineering department or they can be as general as the big problems in the sales system or organization culture. Mathematical modelling provides opportunities for the R&D specialist and management to see the issues in a different way, play with the parameters and make breakthroughs. For instance, assume a big company's logistics tasks where hundreds of employees should interact with each other and make things work. A modeler can see the big picture of the logistics system and make radical changes by simply manipulating the parameters or giving delays to the elements of the system. This can avoid spending much unnecessary resources (both financial and human resources). The bigger the company is the more need is felt for such modellings.

The second important use of the information given in this thesis is for HR department managers. The application of systematic creativity and methods such as TRIZ or mathematical modelling are not limited only to R&D specialist. In fact, all employees must have abilities to see the big pictures and make mathematical models in the direction towards organization success. In many large companies, employees are awarded for suggesting innovative ideas that help the company to progress in the market. Thus, employees with higher abilities of applying math's, mathematical modelling and the required software are preferred.

The above-mentioned abilities should be a must for R&D specialist in addition to the knowledge in their field of expertise. For instance, a R&D specialists for innovation in chemical, mechanical or electrical departments should have a deep knowledge of mathematical modelling and software use as well as experience in the relate field. Furthermore, R&D specialists should have a deep knowledge in multidisciplinary areas of science. Successful R&D managers, technical project managers and CEOs are usually experienced in different science fields. It is of a paramount importance for R&D specialists to be business-oriented and be able to quickly analyze the ideas generated by mathematical modelling or other techniques not to waste time on the ideas imposing huge expenses on the company without return. Today's numerical tests for recruitment examines the simple mathematical and analytical abilities of the employees.

However, for R&D specialist recruitment, particular modelling tasks, visual abilities for innovative ideas and software abilities could provide R&D managers with better information. Also, entrepreneurial mindset and business orientation of the R&D specialist should be examined separately, since they have a sensitive role in companies' growth. The Figure 5-1 represents a concise recommendation for R&D departments.

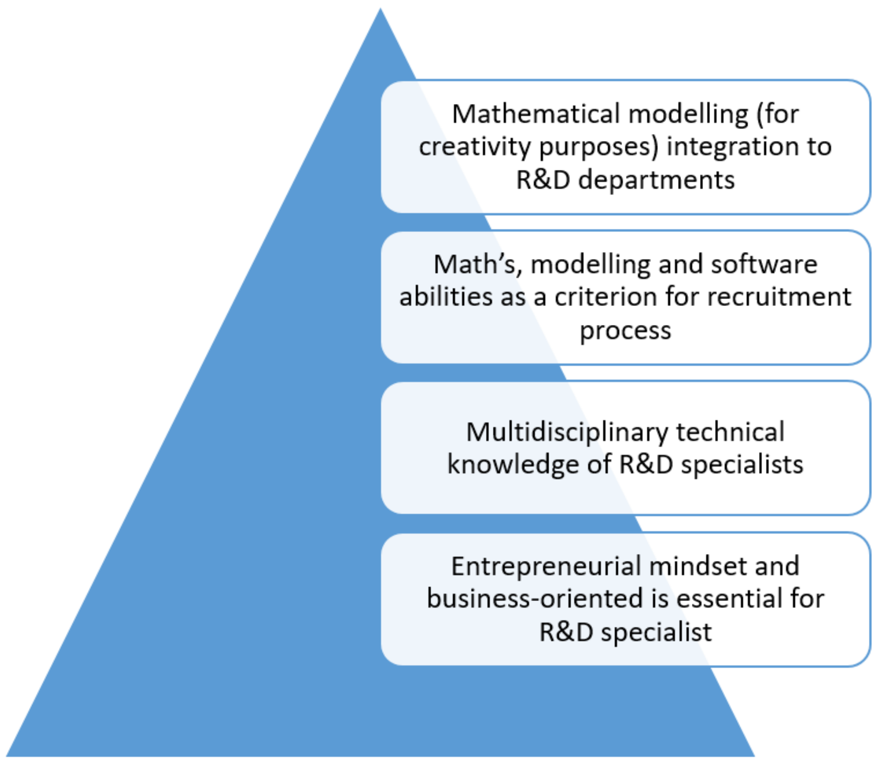

Figure 5-1: Recommendations for R&D departments

5.3. Limitations

There were many technical limitations in this study, which affected the process of the empirical study. Firstly, the area of research was quite new and the literature lacks the required material for a comprehensive study. That was the ground to approach the problem empirically in the beginning without considering the similar literature to the problem. Secondly, the author lacked the required expertise in the chemical process for cement production and in general for mixing and dosing processes (which were the focus of the case study). These affected the process of problem recognition and ideation significantly. Having said that, the interviews with experts in process engineering filled this gap and the results are reliable. Yet, if the author had got the required knowledge in process engineering, the direction of the research could have been of more complexity and closer to the initial beginning point (cement production process). Thirdly, the author was not familiar with MATLAB and Simulink in the beginning of the thesis process. This fact made the fundamental stage of the research longer, though more effective. Fourthly, since the study was conducted in the department of industrial engineering and management, the conceptualization idea for detailed design and prototyping could not be developed further in mechanical and chemical departments laboratories, hence not a comprehensive and detailed economic and profitability analysis could be presented. Eventually, the time restrictions for the completion of the thesis resulted in simplifications of the methods used for the empirical part of the thesis.

5.4. Further research

There could be many research suggestions for further development considering this study. From the technical point of view, the same problem can be scrutinized by process engineers, which in turn may contribute to more complex innovative ideas in mixing, dosing and other chemical processes. Another interesting research suggestion is developing the product (for simultaneous mixing and dosing) by detail design and prototyping. In this way, the comparisons and profitability analysis could be more meaningful and the extent, to which the replacement is profitable would be determined. In many technical and non-technical industries, where the systems can be described by mathematical and differential equations, the same approach could be examined. If revolutions to more systems can be proved, the final stage would be generalization of the approach. The final goal could be discovering an algorithm for the parameters of any system (or defining a category of algorithms for systems), where one is able to radically innovate new systems by making minor changes to the parameters.

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