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Decision support model for wastewater minimization with sequence dependent changeovers application on latex ink production

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Decision Support Model for Wastewater minimization with sequence dependent changeovers:

Application on latex ink production

by

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in partial fulfilment of the requirements for the degree of

Master of Science
in Operations Management and Logistics

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List of Abbreviations

BOM	Bill of Materials
MILP	Mixed Integer Linear Programming
RAW(s)	Raw Material(s)
SKU	Stock Keeping Unit
S&OP	Sales & Operations planning
TSP	Travelling salesman problem

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Preface

This paper presents the results of my research project to receive the master's degree in Operations Management and Logistics at Eindhoven University of Technology, The Netherlands. This research project has been carried out at Océ a Canon Company.

First, I would like to express my gratitude to my company supervisor Emiel van de Rijt for the opportunity to conduct my thesis project at his department. I would like to thank him for his patience and constant guidance since the beginning of my project. Furthermore, I would like to thank several people involved in helping and providing me the information needed to carry out all my research work. Special thanks to my colleagues from PE group, Fillipos, Marianna, and Selma who have not only helped me but have provided me with their companionship at work.

I equally thank my supervisors at the university. Special thanks to Nevin Mutlu for accepting me as her master student. I am grateful for her forthright and helpful suggestions during the period of this work. I also thank her regular feedback and meetings we had to help me overcome the multiple challenges. Next, and no less important, I would like to thank Willem van Jaarsveld and Arun Chockalingham for reading my thesis and providing me with their feedback.

Many thanks to my friends and study mates for all enjoyable moments during my study period. Special thanks to Murat for providing his knowledge and feedback during my project. Last but not least, I would like to express my gratitude to my parents for their patience and never-ending support during all these years. Thank you for allowing me to follow my dreams and become the person I am today.

Nasia Athanasiadou

Abstract

This research project entails the determination of the optimal sequence of recipes for ink making with sequence-dependent changeovers along with the allocation of the raw materials in the available resources. The objective is to develop a decision support model for wastewater minimization. A Mixed Integer Linear Programming Model (MILP) is constructed to support the decision-making process. The performance of the mathematical model is weak for large recipe data set. It presents difficulties in finding the optimal solution in a reasonable computational time. Thus, heuristic and exact models are proposed as alternative methodologies to decompose the problem. The results from the proposed methodologies are analyzed and subsequently compared using three different scenarios. The best scenario is selected to be compared to the baseline. The results obtained using Gurobi Optimizer via the Java interface and Matlab software tools. The numerical results demonstrate the benefits of minimizing the water usage through the appropriate selection of recipe sequence and raw material allocation in the dose lines.

Executive Summary

Industries evolve as time goes by, and the ink industry is no exception. The application of inks in industries such as packaging, food printing etc. has widened considerably and is anticipated to further rise. The market growth is attributable not only to increasing demand of ink portfolio but also to inks with stringent government regulations (i.e. FDA[1]-approved inks for printing food packaging).

Following market trends, Océ has decided to build a new plant (master plant) in Venlo to produce latex ink. Production currently takes places in the pilot plant, but its capacity won't be enough to meet the future demand and requirements. The new building will significantly enhance Océ's ability to meet the growing and diverse needs of the latex ink market.

The pilot plant currently faces several challenges which hinder the full implementation and utilization of the production system. Latex ink is a recipe-based product and is produced in batches. A multi-recipe batch plant such as Océ's is heavily exposed to changeovers. A changeover occurs when production change from recipe "A" to recipe "B". This process requires the changing and cleaning of the equipment using a considerable amount of freshwater. Keeping changeovers to a minimum creates opportunities for lowering the amount of waste water generated. The number of changeovers is driven by the recipe sequencing and the allocation of the raw materials in the dose lines.

Océ aims to apply a policy by means of Lean production principles to reduce the amount of waste water produced. Océ aims to produce the entire ink portfolio following Every Product Every Week (EPEW) policy. This policy requires the development of a fixed production schedule which is applied repetitively on weekly basis. Aligned with the challenges and requirements, the following research objective was formulated:

"What is the optimal recipe sequence and raw material allocation decision for ink production that minimizes the number of changeovers leading to minimal waste water costs under every product every week policy (EPEW)?"

A systematic literature review was conducted to select the most appropriate method to answer the research question. The problem is initially tackled with developing a Mixed Integer Linear Programming (MILP) model which jointly optimizes the recipe sequence and the allocation of raw materials in the dose lines. The optimization was done in Java using Gurobi solver, after which the results are implemented in Matlab and Excel. The NP-hard nature of the problem, however, resulted in exponentially increase number of decision variables. As a result, the solver failed to handle many recipe instances. That motivated the decomposition of the problem in two steps to efficiently solve it.

The first step concerns the partitioning of the initial data set into smaller data sets. The decisions regarding this step basically indicate the level in which the recipe sequence is obtained. Two levels were identified; family level and group level. The next step concerns the linking of the new small data sets as resulted from Step 1. This activity will lead to the composition of one integral recipe sequence including all products. Both steps use a mix of exact and heuristic algorithms. The

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[1] FDA=Food and Drug Administration

advantage of this method lies in fact that a recipe sequenced is acquired sequentially and hence, the complexity problem grows linearly. The proposed methods are examined under three scenarios:

Scenario 1: Data partitioning in a Family Level and static linking of family blocks using TSP

Scenario 2: Data partitioning in a Family Level and static linking of family blocks using Group Technology Heuristic. This scenario results in 3 different sub-scenarios (2a, 2b, 2c). Each sub-scenario reflects a different way of linking families based on their congruency.

Scenario 3: Data partitioning in a Group Level and dynamic linking of recipes using 2 stage MILP model.

The alternative scenarios are compared using as performance indicators the number of changeovers, the total amount of wastewater in kg and the total waste water cost.

Table 1 Resulted Performance of all Scenarios

Scenarios	Total Actual Chgv.	Total Waste [kg]	Total Cost [€]
Scenario 1	25	4000	1613.5
Scenario 2a	24	3645	1473.5
Scenario 2b	25	3835	1533
Scenario 2c	24	3795	1557.5
Scenario 3	21	3300	1368.5

After observing Table 1, it can be concluded that Scenario 3 yields to better results. Therefore, it was selected to be compared with the base line. The base line represents the current way of working in the pilot plant. Scenario 3 was slightly modified to better reflect the current situation where manual instead of automated dosing occurs.

Table 2 Comparison between baseline and modified Scenario 3

Scenarios	Total Actual Chgv.	Total Waste [kg]	Total Cost [€]	Changeovers Savings	Water Savings	Water Cost Savings
Baseline	21	3465	1428			
Scenario 3 (modified)	19	3010	1256	4.85%	13.13%	12.04%

Based on the results, Scenario 3 offers a potential for reducing 12.04% the total amount of waste water cost through decreasing the number of changeovers by 4.85%. It is worth mentioned that Scenario 3 leads to better results even without modifying (decrease) the number of dose lines used. The results prove the potential benefits for Océ if the method followed in Scenario 3 is applied in the pilot plant.

In a dynamic environment, however, it is necessary to have modeling tools that provide solutions quickly. The implementation of Scenario 3 requires the simultaneous implementation of two steps. To obtain solutions more quickly, the MILP model should be directly applied. MILP is unable to handle large data sets. The size of the data set is driven by the multiple allocation options per recipe. Therefore, it is recommended to reduce the number of allocation options either by restricting the number of flex lines or investing on new dose lines. The focus should be placed on the dose lines which generate a big amount of OO waste. This will result in reducing the solution search space for the model and provide a one-step optimal solution.

Last recommendation concerns the strategy for future recipes formulation. The recipe congruency is a factor which stimulates the number of changeovers. Future recipes should be strategically developed based on the common raw materials to obtain a smoother transition between recipes in terms of the number of changeovers.

1 Introduction

1.1 Company Description

Océ-Technologies B.V. is a Netherlands-based company that was founded in 1877 by Lodewijk van der Grinten. It is headquartered in Venlo and operates worldwide in digital imaging, industrial printing and collaborative business services (Ocecareers.com, 2018). Since 2010, Océ joined the Canon Group and work together to take over the leadership in the business printing sector.

Océ offers a wide variety of digital production printing systems depending on the content and size. It is mostly known for the inkjet desktop printers such as VarioPrint which is the biggest in scale of their product range. Over the past years, inkjet printing technology has made great improvements in terms of reproduction speed and print quality enabling the printing of magazines and books on demand. Nowadays, printing moves from paper straight to interior décor and building materials. It offers printing solutions on panels, wood, glass, textiles and wall papers. Furthermore, pilot studies investigate the possibility for printing directly onto copper to produce printed circuit boards using jetting techniques. Océ constantly seeks ways to print 'functionality' (Campus & partners, 2018).

Figure 1 Océ VarioPrint 300[2]

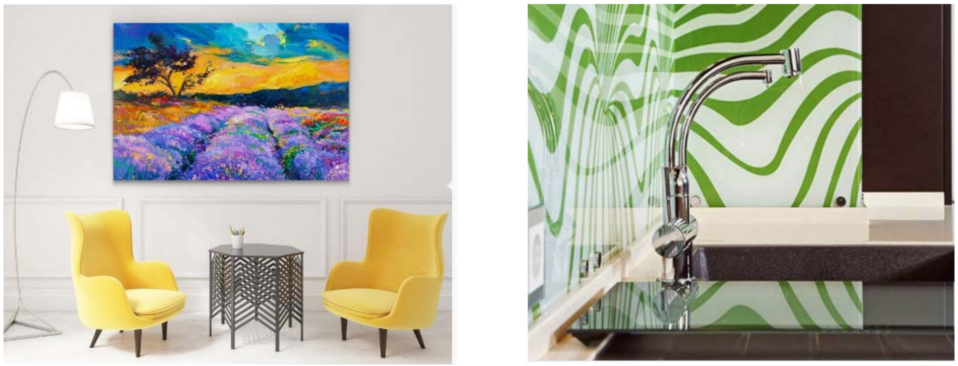

Figure 2 Printing Applications on Canvas and Building Material (glass)

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[2] Canon varioPRINT 300 - Black and White Production - Canon Europe. Retrieved from: http://whattheythink.com/articles/72603-production-inkjet-next-wave-canon-oce-varioprint-i300-sheetfed-inkjet-press-more/

1.2 Problem Context

Océ currently produces latex ink in the pilot plant that was built in 2016. Latex ink is a eco conscious water-based ink where pigments are dissolved by resins in water instead of using solvents (Mimaki, 2018). The pilot plant initially was used for research objectives to verify the processes and make decisions regarding innovative technologies. Nowadays, it is also used for producing small volumes of ink and successfully meets the market's demand. The purpose of the pilot plant is to take advantage of this learning period and generate data.

The ink industry, however, continues changing and the scope of inks application has widened considerably. The market growth is attributable not only to increasing demand of ink portfolio but also to inks with more specific requirements (i.e. FDA[3]-approved inks for printing food packaging). In a couple of years, the pilot plant won't be sufficient not only to cover the demand but also meet the new standards effectively. Therefore, Océ has decided to build a new plant (*master plant*) for latex ink production in Venlo. The master plant will be equipped with new upgraded equipment and provide automated solutions compared to the pilot plant to better serve the interests of the company. The expanded latex production plant will significantly enhance Océ's ability to meet the growing and diverse needs of the latex ink market.

Despite the marked improvements in the pilot plant regarding production processes, there are still some challenges hindering the full implementation and utilization of the production system. The challenges regard the allocation of the raw materials in the dose lines and the recipe sequencing. Ink is produced in batches according to recipe instructions. Each recipe has specific raw materials and equipment requirements. A multi-recipe batch plant such as Océ's is heavily exposed to changeovers which are associated with changing and cleaning the equipment.

In this setting, the set of dose lines is the equipment component where the most changeovers occur. Therefore, the focus of this research is placed on this set. Dose lines are used for loading the raw materials that used by a recipe. The number of dose lines in the pilot plant is less than the number of raw materials leading to frequent changeovers. Dose lines can be characterized as dedicated or variable. Dedicated dose lines are used for the dosing of specific raw materials whereas variable dose line can accommodate the dosing of different raw materials. The variable dose lines introduced flexibility in the system but increase the complexity as well. According to the recipe ingredients, each recipe may use both dedicated and variable dose lines. As a result, a recipe doesn't have a unique representation in the system from allocation point of view. It is represented as a set of recipes instead. The set size depends on the number of all possible allocations in dose lines resulted given the permittable combinations as arise from the dedicated and variable dose lines. The allocation on the dose lines in the pilot plant is currently done based on best guesses. So, given that the number of raw materials and recipes have a linear but not proportional relationship the current way of working will not be sufficient in the future.

As mentioned, changeovers are also associated with cleaning the equipment. When production moves from one product to another, the equipment must be cleaned by being flushed with fresh water or by a mix of water and liquids. Frequent changeovers imply reduced equipment availability

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[3] FDA=Food and Drug Administration

and increased clean water demand, thus wastewater generation. To address this problem, Océ aims to apply a policy by means of Lean production principles. Lean thinking was first introduced during eighties and used for the development of the Toyota Production System (TPS) in Japan. It focuses on maximizing the process velocity of a product or service through the elimination of unnecessary delays, loops and waste. Lean practices have been applied to wide range of business areas (manufacturing and non-manufacturing) gaining popularity over time. According to Shah and Ward (2007) *"Lean Production is an integrated socio-technical system whose main objective is to eliminate waste by concurrently reducing or minimizing supplier, customer, and internal variability*".

To achieve a lean product development, Océ has decided to implement a fixed cyclic production schedule known as Every Product Every Interval (month/week/day) (EPEx) principle for ink manufacturing. Océ wishes to produce the entire ink portfolio following Every Product Every Week (EPEW) policy. According to the literature, "*EPEx is a lean production control method that involves creating a fixed cyclic plan through the levelling of product volume and mix, with a continuous focus on setup reduction."* (Powell, Alfnes, & Semini, 2010). Traditional manufacturing systems do not operate with repetitive production patterns. Fluctuations in demand, in production rates, completion times and product flow result in. erratic production schedules with unfavorable production sequence leading to waste (Packowski, 2014).

The basis of EPEx principle is to make each production cycle as small as possible. Cyclic schedules contribute to production leveling and improve system's efficiency (Fauske et al, 2008). This can be achieved by gradually reduce batch sizes and doing as many changeovers as are feasible. Figure 3 demonstrates the stages of development in every product every day plan.

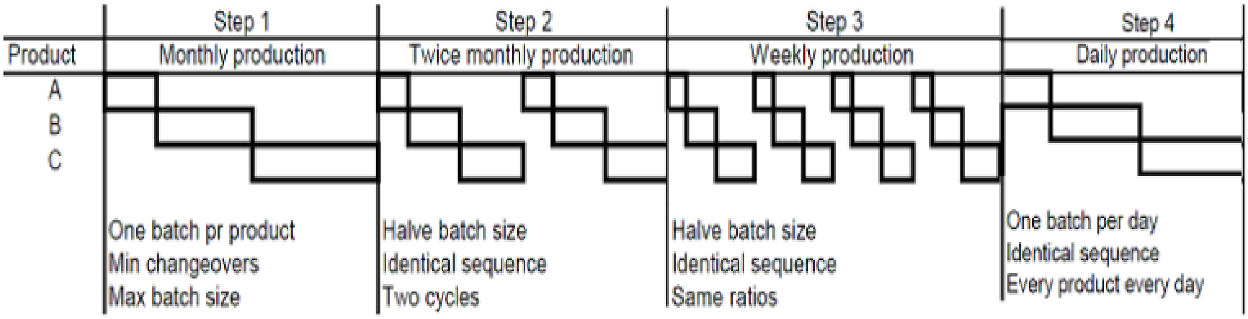


Figure 3 Stages of development in EPE (Glenday and Sather, 2005)

The pilot plant currently produces every product every 8 weeks (EPE8W). The production schedule is demand driven. The Logistics department clusters demand and the pilot plant produces ink in multiple batches. Changes in demand result in frequent production changes and rush orders.

As resulted, the total number of changeovers occur in the system, thus the waste water volume, depends on the recipe sequence (also known as *sequence dependent changeovers*) and the allocation of the raw materials in the dose lines. Hence, the problem of the pilot plant can be solved by developing a model that minimize the number of changeovers following EPEW principle by jointly optimizing the recipe sequence and the raw material allocation in the dose lines. As mentioned, a

EPEx policy applies results in many changeovers overall because it applies repetitively a fixed schedule of specific interval. So, the focus of this research is to obtain the fixed schedule that leads to the minimum number of changeovers.

1.3 Research Objective

The aim of this research project is to provide a decision support model for recipe sequencing with sequence-dependent changeovers. Simultaneously, the model provides the optimal allocation of raw materials in the dose lines for each recipe. The objective is to minimize the wastewater costs.

1.4 Research Questions

Aligned with the motivation of this study a research question which summarizes the scope and the research area of this project is formed.

"What is the optimal recipe sequence and raw material allocation decision for ink production that minimizes the number of changeovers leading to minimal waste water costs under every product every week policy (EPEW)?"

To answer this question in a structured manner a set of sub questions has been formed. Answering these questions step by step will lead to a smooth and efficient analysis.

1. What is the current production strategy for the production in the pilot plant?
2. What are the resulting performance levels under this strategy and the target levels set by the company for the master plant?
3. How can the performance of production system be optimized by scheduling the recipe sequence?
4. What are the expected benefits for the company, if the proposed production schedule is applied?

1.5 Research Contribution

This research projects aims to contribute to: (i) the development of a mixed integer mathematical model (MILP) that jointly optimizes production recipe sequencing and allocation of raw materials per recipe with respect to limitations in resource availability, (ii) the development of multiple heuristic models to address to the NP-hard nature of the scheduling problem , and (iii) to provide some insight into wastewater cost minimization in batch processes. The minimization of wastewater cost is achieved through minimizing the number of changeovers in a sequence dependent production environment.

1.6 Research Methodology

This section presents the methodology adopted in the Master thesis. This project is carried out following a well-established problem-solving framework proposed by van Strien (1997) and Joan Ernst van Aken (2007), the problem-solving cycle (PSC). It's a five step PSC which includes: problem definition, analysis, design, intervention, and evaluation. The last two steps (Intervention and

Evaluation) are not included within the scope of this research due to the limited duration of the project. The representation of this framework is given in Figure 4.

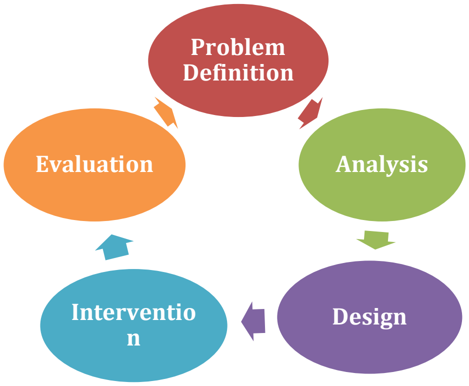


Figure 4 Problem-solving cycle (van Strien, 1997)

Problem Definition: The aim of this step is to clearly define the research problem of the master thesis project. This step requires to identify the weaknesses of the current situation. The implementation of this step results in determining the main production scheduling problems of the pilot plant.

Analysis: This step aims to answer the first two research questions. To execute this step, it is essential to analyze the relevant information of the current production system and identify the roots or bottlenecks of the problem.

Design: This step concerns the development of a Mixed Integer Linear Programming (MILP) model to aid the decision-making process for the recipe sequencing problem. This model would provide an optimal production sequence with respect the number of changeovers and the appropriate allocation decision regarding the raw materials. The results of the model are used to answer the remaining research questions.

1.7 Confidentiality

For confidentiality reasons, the exact information regarding costs, production capacity and recipe ingredients have been modified in this public version of the report. However, this does not affect the conclusion or recommendations of the report. The involved parties, university supervisors and Océ, are the only ones supplied with the real data.

1.8 Thesis Outline

The remainder of this report is structured by first presenting a brief overview of the existing relevant literature review. Next, Section 3, focuses on the analysis of the current situation at Océ providing information regarding the production and scheduling process. The conceptual model that introduced to address the problem is presented in Section 4. The section also provides the mathematical model developed including the model assumptions and implications. The methodology used to decompose the problem along with the different solution methods is presented in Section 5. This approach resulted in the development of three alternative scenarios under investigation and their numerical results are compared in Section 6. The results after comparing best scenario to the base line are provided in Section 7. Finally, the conclusions, recommendations, and suggestions for future research are presented in Section 8.

2 Literature

The aim of this Section is to provide a brief overview regarding the existing literature in production scheduling with sequence dependent changeovers in a flow shop environment.

2.1 Scheduling in Batch Processes

The layout of ink manufacturing department shares characteristics of a flow shop environment. The scheduling problem in a flow shop environment is defined by a set of n jobs J = {1, 2, … , n} and a finite set of machines M = {1, 2, ..., m}. Each job $j \in J$ consists of a finite set of subtasks n_i (called *operations*). The processing of an operation must be executed on a predetermined machine, for example the i_{th} operation of job j, denoted by O_{ij}, is processed on machine $m_{ij} \in$ M. The aim is to find a schedule for processing assigning the m machines to n jobs/tasks, denoted, to execute all jobs under the imposed constrains (Blazewicz, Ecker, Pesch, Schmidt & Weglarz, 2007).

In general, flow shop problems are easy to conceptualize, but remarkably complex to be solved, from a mathematical and computational perspective. The computational complexity of scheduling problems led to the characterization of many scheduling problems belong to the NP-hard class ((Gupta and Darrow, 1986); (Cheng et al., 2000)). The NP hard class is defined as *"the complexity class of decision problems that are intrinsically harder than those that can be solved by a nondeterministic machine in polynomial time."* (Pieterse & Black, 1999).

Despite strong computational resources nowadays, only small to medium size problems are suitable to be solved by exact methods. As the number jobs of jobs increased, the problem becomes combinatorial and approximate optimum solutions are more favored for such problems. Since, there are not known polynomial time algorithms to solve most of those scheduling problems in optimal way, researchers have mostly placed the focus on developing approximation techniques. The most common techniques used can be divided into three categories: (1) *exact algorithms*, (2) *approximation algorithms,* and (3) *heuristic algorithms.* These techniques might lead to near optimal solutions but run in polynomial time.

2.2 Setup cost/time considerations in flow shops

The first systematic approach to scheduling problems was undertaken in the mid-1950s. Johnson (1954) has considered a two and three stations flow shop problem and developed an exact algorithm (Johnson's-rule) for n tasks with objective of makespan. The algorithm generates a permutation schedule, in which each machine processes the jobs in the same sequence. After the pioneering paper of Johnson's, a plethora of flow shop scheduling problems have appeared in the literature from numerous researchers ((Allahverdi et al., 1999); (Graham et. al., 1979); (Gupta, 1971) and (Lawler et al., 1993)). However, most of these papers assumed negligible setup times or disregarded part of processing times. Pinedo (2008) showed that neglecting setup times can decrease the efficiency of the machines for more than 20%.

The setup times in scheduling problems were first appeared in the literature after mid-1960s as a separate cost. The first comprehensive survey paper on scheduling problems with separate setup times/costs considerations was conducted by Allahverdi et al. (1999). He cited around 200 papers that deal with setup issues the concept of set up time between two machines for different shop environments in both static and dynamic problem settings, but most were published before the 1990s. They concluded that more research should focus on objectives related to due dates. Since then, their research has been updated twice Allahverdi et al., (2008, 2015). The survey that carried out in 2008 contains more than 300 papers which published from 1999 to 2006 and the one published in 2014 provides an extensive review of about 500 papers that have appeared since the mid-2006 to the end of 2014 for each environment setting; static, dynamic, stochastic, and deterministic. More recently, Neufeld, Gupta, & Buscher (2016) published a comprehensive review on group scheduling and described the solution methods that has been conducted so far.

According to Allahverdi et al (2008). scheduling problems with setup times are classified as sequence independent or sequence dependent as well as batch and non-batch. The definition of a batch is as follows. Jobs are divided into F, Families, (F>1). Batch is defined as a set of jobs of the same family that can be processed together. In a batch processing environment, (i.e. pallets, containers, boxes), a batch setup time occurs when there is a switch from processing a job in one batch to a job in another batch. During processing in a non-batch environment, a setup time is occurred preceding to the processing of each job. A batch it is sequence-dependent when it's set up time for a batch x depends on which product was setup on the machine prior to running x. So, it depends on the families of the current and the preceding batch. In contrary, a batch is sequence-independent if the set-up time depends only on the family of the current batch to be processed.

Potts and Kovalyov (2000) surveyed more extensive literature on scheduling problems with batching and scheduling that is now available. They the problems with batch considerations into problems which are solvable in polynomial or pseudopolynomial time or are binary or unary NP-hard. They highlight the importance of using dynamic programming as a method for solving scheduling and batching problems.

Some reviews, such as Cheng et al. (2000) focused on static and deterministic flow shop scheduling involving setup and/or removal times. They classified the existing literature into four broad categories; sequence independent job setup times, sequence dependent job setup times, sequence independent family setup times, and sequence dependent family setup times.

Surveys also conducted regarding scheduling problems which include batching and lot sizing decisions. Based on the observation that scheduling models rarely consider batching and lot sizing models sequencing issues Potts and Van Wassenhove (1992) provided a literature on this field. They examined computer integrated manufacturing environments, where batching and scheduling decisions need to be controlled by the same computer. Drexl and Kimms (1997) and Karimi et al. (2003) examined capacitated, dynamic, and deterministic cases for scheduling and lot sizing problems from inventory management perspective. The authors conclude the necessity to examine further problems that combine scheduling and batching cost.

During 1999 to 2006 has been a significant increase in interest in scheduling problems involving setup times (costs). Bigras et al. focused on scheduling problems on a single machine with sequence dependent setup times. They tackled it as time-dependent travelling salesman problem (Bigras et al., 2008). Yi and Wang (2003) proposed a tabu search algorithm for scheduling grouped jobs on parallel machines. For the same problem, Chen and Powell (2003) suggested column generation-based branch-and-bound algorithms, obtaining optimal solutions for problems up to 40 jobs, 4 machines and 6 families, and Yi et al. proposed a fuzzy logic embedded genetic algorithm. Dunstall and Wirth (2005) suggested several simple heuristics as well for the same problem.

The flexibility and applicability of flowshop scheduling has led to a very active research in several industries. These are industies such as the electronics, automobile, textile, chemical manufacturing (Zandieh et al., 2006; Mirsanei et al., 2010), label sticker manufacturing (Lin and Liao, 2003), furniture manufacturing (Wilson et al., 2004), tile industry (Andrés et al., 2005), food processing, casting operations (Hans & Van de Velde, 2011), pharmaceutical (Stadtler & Sahling, 2013), iron and steel (Pan et al., 2013), packaging (Adler et al., 1993), and paper industries (Gholami et al., 2008).

Up to now most research has focused on minimizing the makespan (or maximum flow time) while few papers have dealt with objectives involving the due dates of jobs ((Grabowski et al., 1983); (Sen et al., 1989); (Yeong-Dae Kim, 1993); (Zhu and Meady, 2000)). Lately, the interest in wastewater minimization has started becoming more important in the processing industry due to an increase in environmental awareness.

The techniques used for solving the wastewater minimization problem in batch plants are either graphical techniques or mathematical techniques. The graphical techniques are used in production environments where the reuse of waste is restricted to a single contaminant and fixed schedule. These techniques require the starting and finishing times to be known to determine a fix production schedule. As a result, the resulted schedule is associated with a specific wastewater target that might not be the absolute minimum. Graphical technique examined by Wang & Smith (1995), Foo et al. (2005), Majozi et al. (2006), Chen and Lee (2011), Kim (2011) and recently, by Chaturvedi and Bandyopadhyay (2014).

The mathematical techniques on the other hand, determine the wastewater target simultaneously with the schedule. Thus, they have the advantage of dealing with multiple contaminant systems. Researches who addressed to the problem using mathematical techniques are: Almató et al., 1999, Grau et al., 1996; Majozi, (2005), Gouws and Majozi (2008), Adekola and Majozi (2011), and Nonyane and Majozi (2012)).

3 Description of Production and Scheduling Process

This section describes the current production and scheduling system at Océ. Section 3.1 starts with providing an overview of the latex ink characteristics and its production processing steps. It also presents an overview of the associated costs. Next subsection presents the current production scheduling system in the pilot and sets the scheduling requirements for the master plant. The implications derived from the analysis set the scope of research in terms of the resources under consideration.

3.1 Production system analysis

3.1.1 Ink Formulation and Characteristics

Printing ink is a recipe-oriented product and its manufacturing receives a great attention in the chemical industry. In general, the ink ingredients can be classified in three main categories: pigment, vehicle, and modifiers/additives (Onlineprintfile.com, 2018):

1) **Pigments.** Pigments are solid substances used for coloring matter. They can be found in the nature or produced synthetically. Their consistency can be powdery, liquidity or concentrated paste. The scope of application defines the type of pigment that can be used. For instance, food packaging, a nontoxic ink is required due to the direct/indirect contact with the food content (Printing Ink, 2003).

2) **Vehicles.** Vehicle is a mix of several components in the ink which carries the pigment and binds it to the printed surface. This mix can be composed by petroleum or vegetable oils, water, or solvents. The vehicle is paired with pigments which are difficult to work with alone.

3) **Modifiers/Additives**. The purpose of using modifiers and additives is to the change the ink properties to be used in several applications and processes. Can be categorized in:

- **Driers**: accelerate the drying process of the ink.
- **Waxes**: improves the slip and scuff resistance of the ink.
- **Anti-skinning agents**: prevents ink from drying too fast and the formation of surface film.
- **Extenders**: increase the coverage of the pigment in the ink.
- **Distillates:** improve the flow of ink.

The type of ink that is produced in the pilot plant is called **latex ink**. Latex ink, also called resin ink, is a new concept of ink that uses a water-based vehicle with heat-cured resins (polymers) and additives (co-polymers) (Fespa, 2016). Latex ink is an eco-conscious ink. Pigments are dissolved by resins in water instead of solvents which results in odor reduction. Since, it has low Volatile Organic Compounds (VOC) emissions the use of special ventilation in the workplace is redundant; hence, it reduces operator health effects (Mimaki, 2018).

3.1.2 Product Portfolio

Stock Keeping Unit (SKU) refers to an item of stock that is described in relation to the characteristics of the end product (Silver et al., 1998). In Océ the determinants of the SKU are the recipe and the can size used per product.

The product portfolio of latex ink consists of 22 SKUs which can be either *Inks* or *Primers*. The final products are perishable (up to 18 months of shelf life) and are produced in batches. Each batch processes a single recipe and a setup is required when switching to another recipe.

A recipe indicates which raw materials (RAWs) should be combined to produce a specific ink type or primer. The inks that are currently produced are based on a total of 25 raw materials, with a max of 12 raw materials per a single recipe. Recipes are clustered into four large groups (*Families)* according to their properties and Bill of Materials (BOM). These groups are: *Family A, Family M6, Family M7* and *Family CL*. Each family includes both primers and inks. The demand for inks is relatively higher as opposed to the primers. The production of primers, however, is indispensable because they used as adhesive agents between the substrate and the printing ink to prevent the in between extreme absorption. Therefore, it was decided to formulate a dedicated family (*Family P*) by isolating the primers from each family. In other words, recipes of *Family A, Family M6, Family M7* and *Family CL* belong to the "Ink Families" whereas recipes of *Family P* belong to the "Primer Family". Figure 5 depicts the product scope of the latex that is currently produced in the pilot plant.

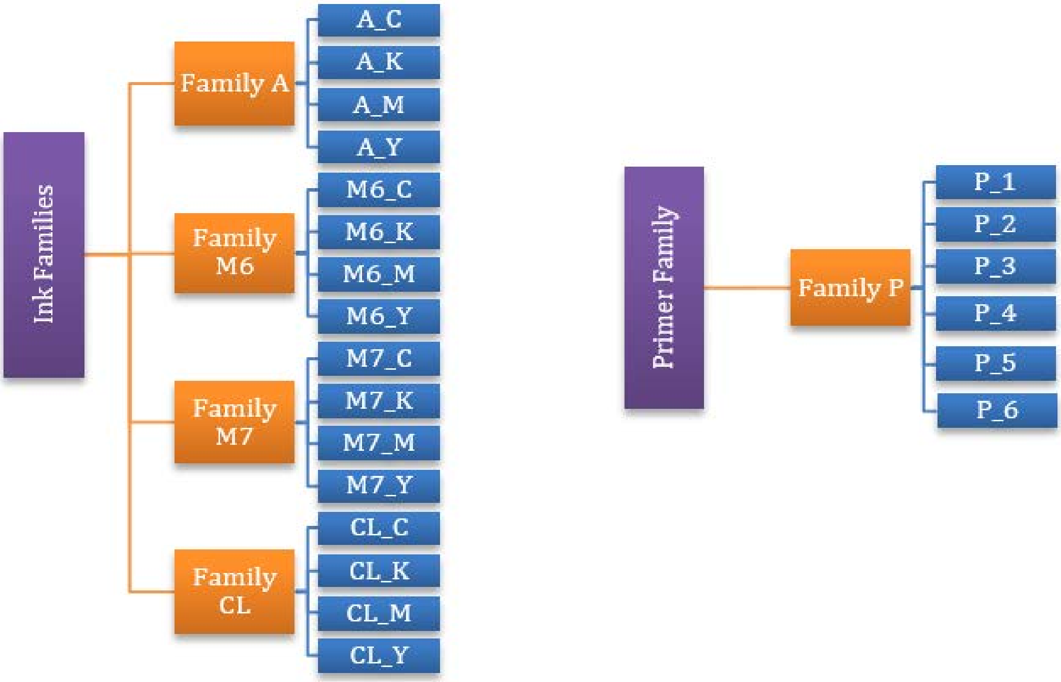


Figure 5 Product Scope of Latex Ink

Color printing typically uses ink of four colors: Cyan (C), Magenta (M), Yellow (Y) and Black (K-"Key"). Therefore, the end products of Ink Families are basically inks of each color type. In order to distinguish the different inks types across the families, the end products are named according to their color and family initials which belong. For example, the recipe A-C represents the ink that is produced by Family A in color cyan (C).

3.1.3 Production Process

3.1.3.1 Background Information

Before presenting the production layout, it is essential to provide the terminology and equipment that are used to represent the production system. Table 3 provides a brief explanation of the used terminology and Table 4 presents the description of the equipment that is used in the production process.

Table 3 Basic Terminology

Terms	Description
Mixing/Blending	- These terms are commonly interchanged. The term mixing is typically reserved to describe the combining of dry and wet raw materials whereas blending for the combining of dry materials ("Tips & Techniques for Mixing & Blending Success (Part I)", 2018). - The ink nature constitutes mixing as the most appropriate term but occasionally blending can be used as well.
Dosing	- The process of adding raw materials in measured doses to a container (or vessel).
RAWs	- Raw materials that are used to produce ink. These could be pigments, wax etc.
Cleaning	- A cleaning solution method is applied to clean the interior surfaces of vessels, process equipment, pipes, filters, and associated fittings, without disassembly. - It uses a mix of chemicals, heat and water. - This method is widely used in hygiene critical industries, such Food, Beverage and Pharmaceutical (Vogel Communications Group, 2018). - The current system uses demineralized water.

Table 4 Basic Equipment

Equipment	Description
Mixing Vessel	- Container where the RAWs are dosed and mixed.
Dosing lines	- Tubes that allow the raw materials to travel to the dosing point.
Buffer tanks	- *"A buffer tank is a unit where the holdup (volume) is exploited to provide smoother operation."* (Faanes & Skogestad, 2003) - The buffer tanks are usually installed between batch process units to allow their independent operation.

Intermediate Bulk Container (IBC)	- Container for the storage and transport of bulk liquid ingredients. - Are used for the store of pigments (Y, M, C, K).
Dosing Tube	- Tube to which the cleaning fluid tanks and dosing lines are attached with valves. - Dosing tube enables the dosing in the two mixing vessels.
Valve	- Device which opens and closes in order to control the flow of liquids.

3.1.3.2 Pilot Plant

Latex ink is produced in batches in three consecutive stages. As each stage is incorporated in different station, we can distinguish three production stations; *Dosing and Mixing station (D&M)* (hereafter, component production), *Filtering station (F)* and *Filling and Packaging station (F&P)* (hereafter, final production). Figure 6 depicts the consecutive production steps for ink production and Table 5 the equipment which is used.

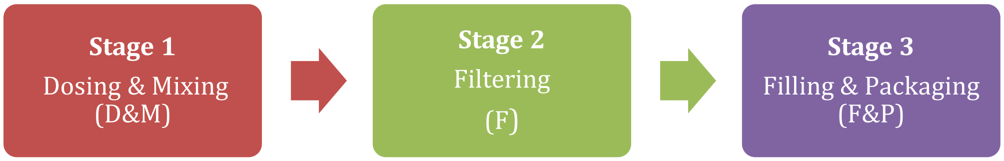


Figure 6 Production sequence in the pilot plant

Table 5 Pilot's Plant Equipment

Basic Equipment
1. Small mixing vessel
2. Large mixing vessel
3. Demi water buffer tank
4. Buffer tank for cleaning
5. Small buffer tanks with dose line (A2, A3, A4, A5, A6, A7)
6. Connections for drums or IBC's with dose line (S2, L2, PF1, PF2, PF3, PF4)
7. Big buffer tank with dose line (L1)
8. Melting tank with dosing line (S4)
9. Filtering and Filling line
10. Dosing tube to enable dosing in the two mixing vessels

- **Dosing and Mixing station (D&M)**

  The Dosing and Mixing station is a recipe driven processing stage that requires most of the manufacturing resources. In this stage, an extensive use of buffer tanks, pipes, dosing tubes, valves, pumps, and mixing vessels is required.

A valve at the bottom of the vessel allows the mixture to be transferred either to the *F&P* station or to waste containers. The path is defined by the operation mode of the system, processing or cleaning.

- **Filtering station (F)**
  The ink is filtered according to the recipe's requirements. The station's throughput is determined by the amount and size of filters that each recipe needs. The vessels in the master plant have an inline filtration system (filters are placed directly after the vessels); no buffer time till the ink to be filtered. However, after filtering it is necessary to add a buffer tank to pressurize the ink for filling purposes.

  Each time that the consecutive batch is different from the previous processed (different color) the filters need to be cleaned. The filters require manual cleaning, but the cleaning of the equipment is done automatically.

- **Filling and Packaging station (F&P)**
  The ink flows from the filtering station to a filling device. In this stage the process is fully-automated. When the products are ready are shipped off to logistics and distributed accordingly.

3.1.4 Production Process

Before the production starts, the dosing lines to be used should be either clean or filled with the correct raw material. The mixing vessel, filters and filling line need also to be cleaned to residues from the previous batch.

Production starts by first adding demineralized-water. This will be circulated over the dosing. Before adding any raw material, a circulation needs also to be done on each involved dosing line. If the dose line was filled already with the required raw material, circulation will be short. If the raw material is new, then a long circulation is needed. Note that some raw materials are dosed manually due to the insufficient number of dosing lines. When the dose line is circulated accordingly, it can be used afterwards to dose the raw material into the mixing vessel through the dose tube following the recipe instructions. Some materials can be dosed simultaneously (parallel dosing) whereas some cannot and need to be dosed in sequence (sequential dosing). The raw materials are processed till become a homogeneous fluid. When the ink is ready, it is filtered and filled into cans. After a batch finishes, the system needs to be cleaned again (van der Schriek, 2018).

3.1.5 Production Systems Costs

3.1.5.1 Machines Costs

Machines costs usually divided into fixed costs, operating costs, and labor costs. *Fixed costs* occur independently of the rate of work. Such as costs are: equipment depreciation, interest on investment, taxes, storage, and insurance. Those costs are spread evenly during the year even when machines stop working. *Variable costs* are related directly to the rate of work. As a result, are calculated per hour for actual usage of the equipment. *Labor costs* is a cost component that can be included either in machines costs or independently. Labor costs are associated with employing labor and are driven by the number of shifts. At certain point, labor costs can be considered as fixed since the working hours are already predetermined by Sales & Operations planning (S&OP) process.

The pilot plant operates 16/5, in 8-hour shifts; but generally, the number of shifts can vary. Hence, in this case labor costs are semi-fixed (Food and Agriculture Organization of the United Nations, 1992).

3.1.5.2 Changeover costs

Changeovers consider being a critical operation in the manufacturing companies (Gungor & Evans, 2015). These costs are commonly neglected in industrial practice but can bring substantial economic benefits once are treated accordingly. Changeovers costs can be expressed in terms of labor costs (extra shifts, lost capacity, etc.) and scrap costs (material waste, water waste, etc.). It is a set of necessary but non-value adding activities. The cleaning of the equipment units, such as pipes, mixing vessels etc., it is an indispensable process to ensure the cleanliness of the system, product safety and protect brand reputation (Fryer & Asteriadou, 2009). However, it causes disruption of the system and generates waste water. Cleaning duration depends on whether the setup is *minor* or *major*. Minor set up occurs when two consecutives have high compatibility. In contrast, major set up can occurs when switching between families and can take several hours e.g. cleaning and sterilization of the equipment.

Changeover costs usually divided into fixed cost and variable cost. In this setting, the fixed costs are associated with the cleaning of the specific parts of the system. These concern the cleaning of the vessels, filling and packaging line. The cleaning of these parts is fixed (hence, the associate cost) and takes place always when production switches to different recipe. The amount of dose lines, however, that need to be cleaned is not fixed. It depends on the number of dose lines that is used per recipe. So, in this context it is considered a variable cost.

Changeover costs are calculated based on a *changeover matrix*. A changeover matrix provides information regarding the time or the cost of setup conversions on a resource. In the examined case, the changeover matrix reflects the number of changeovers occur in the dose lines (both dedicated and variable) when switching from a recipe A to a recipe B according to their raw material allocation. Table 6 presents an example of how a changeover matrix is appeared in the examined setting. For example, moving from recipe A_K to C_K will result in 4 changeovers in the dose lines.

Table 6 Changeover Matrix Example

Changeover Matrix	A_K	A_Y	C_K	C_Y
A_K	0	3	4	2
A_Y	3	0	8	2
C_K	3	3	0	6
C_Y	6	10	4	0

In conclusion, changeovers are a critical cost component of the manufacturing environment especially where a wide range of products need to be produced. There are a lot of benefits when they are considered. In this setting, their calculation becomes challenging. The total changeover cost is a combination of recipe sequence and raw materials allocation in the dose lines.

3.1.5.3 Waste Water costs

The waste water costs are estimated using the same concept applied to calculate the changeover costs. Hence, waste water costs are also divided into fixed and variable costs. The fixed cost component is associated with the cleaning of the vessels, and the filling and packaging line whereas the variable cost component is reflected by the cleaning of the dose lines.

The waste water cost is directly dependent on the number of changeovers. However, they have linear but not proportional relationship. The amount of waste depends on which set of dose lines the changeovers occurs. Dose lines can be divided in 3 different sets. *Set 1* contains the A lines (A1, A2, A3, A4, A5, A6, and A7), *Set 2* contains S and L lines (S2, S4, L1, and L2) and finally *Set 3* contains pigment lines (PF1, PF2, PF3 and PF4). The cleaning of each set generates different waste water volume. Two types of waste water are generated; *OO waste* and *waste for the sewer*. OO waste it is a mix of (almost) pure raw materials from the draining system and the rejected product. As a result, it is a highly polluted waste that requires additional processing before disposal. This procedure is associated with an extra processing cost (70 cents per kilogram generated). The second type of waste (*waste for the sewer)* doesn't require additional process hence, costs. As a result, the waste water costs are directly impacted by the amount of OO waste generated. Table 7 summarizes how waste water can be estimated.

Table 7 Waste Water Matrix

	Total [kg]	**OO Waste [kg]**	**Sewer Waste [kg]**
Code 1 – PF lines (from pigment to pigment)	100	45	55
Code 2 – PF lines (from any raw material to pigment)	175	120	55
Code 3 - A lines	115	40	75
Code 4 - L, S lines	190	85	105

In this research setting, the priority is given to the estimate the wastewater costs. Therefore, the machine costs were set out of scope. As a result, the decision-making process will only be influenced by the number of changeover that occur and then translated in terms of waste water cost. Intuitively, the bigger the number of changeovers is the higher the associated costs. The aim of the study will be to generate a sequencing model with an objective to reduce the total number of changeovers, hence waste water costs.

3.2 Scheduling System Analysis

3.2.1 Production Scheduling in the Pilot Plant

The production schedule of the pilot plant is demand driven, and the planning is made by the Logistics department on a weekly basis. Demand is clustered according to families and the allocation of the raw materials in the dose lines is made based on best guesses. Currently, the pilot plant can produce on average every product every 8 weeks (EPE8W).

The sequencing of production is a complex activity due to its combinatory nature. An attempt to examine the impact of changeovers in the systems was previously made by company by examining the effect of three production strategies on the system using different performance indicators. The results obtained by performing simulations for each production schedule for one year (van der Schriek, 2018). Table 8 provides the performance of the pilot plant under three different production schedules:

- Schedule 1: *Produce each ink type of a certain kind once before moving to the next ink type*;
- Schedule 2: *Produce each ink type of a certain kind twice before moving to the next ink type;*
- Schedule 3: *Produce a predicted monthly demand in one production schedule*.

Table 8 Production of the Pilot Plant (Simulation results)

	Schedule 1	**Schedule 2**	**Schedule 3**
Output/week (cans)	2665	2986	3200
Amount of Batches	476	533	570
Amount of Cans	139,367	155,884	166,752
Average Processing Time (hr)	11,5	12,7	11,5
Average Effective Processing Time (hr)	18,5	16,7	15,5
Raw Waste (Tons)	5	2,6	0,9
Water Waste (Tons)	226	233	230

3.2.2 Production Scheduling in the Master Plant

By the time that master plant will be operational, the number of recipes will have already increased (2 new Families; Family MG and Family AL). This means that new RAWs will be added to the system increasing the complexity of the corresponding scheduling problem.

The target for the master plant is to produce every product every week (EPEW). Master plant will be equipped with sufficient number of dose lines to accommodate all the raw material that currently is handled by the system. The new equipment of a bigger capacity will increase production and the application of new production techniques (i.e. automated dosing and cleaning system) will enable the fulfillment of EPEW target relatively easy.

4 Model Development

The aim of this research is to find an optimal recipe sequence and raw material allocation per recipes based on which waste water generation is minimized under an EPEW production strategy.

Section 4.1 presents the conceptual model constructed to solve the problem using a two stage approach explained in Section 4.2. Section 4.2.1 explains in detail the procedure followed in Stage 1 to generate all recipes in the system and calculate the changeover matrix. Subsequently, Section 4.2.2 presents the mathematical model proposed to solve the sequencing problem and the implications of its implementation.

4.1 Conceptual Model

The analysis of the system in terms of production (Section 3.1) and scheduling (Section 3.2) enabled the conceptualization of the problem. The conceptual model serves as a roadmap for all steps taken to the obtain the final solution. As can be derived from Figure 7, a two-stage approach was selected as a methodology to address this problem. The two-stage method is a sequential procedure, where Stage 1 is carried out first and its results are subsequently used as an input for Stage 2.

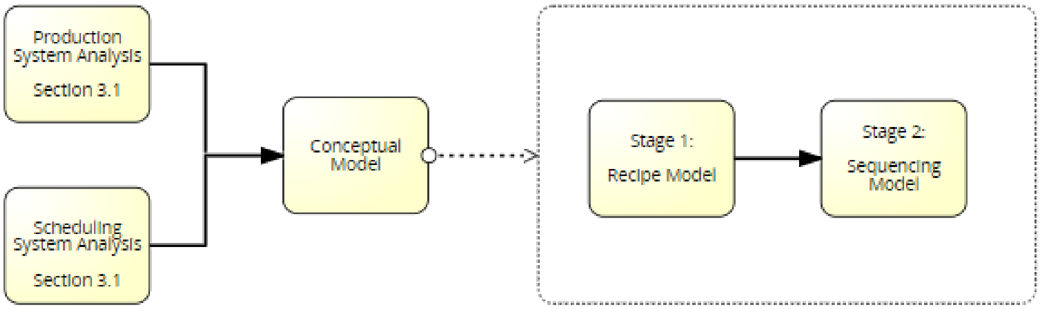


Figure 7 Completion of the fundamentals of the conceptual model

The objective of *Stage 1* is to completely enumerate the possible allocation options that a recipe generates given the allocation restrictions in dose lines. This process is encapsulated in the *Recipe Model.* The output of the recipe model is a list that contains all possible allocation options per recipe in the system. This list is used as an input file for the next step.

The objective of *Stage 2* is to find the sequence of the recipes that minimizes the number of changeovers. This process is encapsulated in the *Sequencing Model.* So, the output of this model will be a sequence of 22 recipes which results in the minimum number of changeovers.

The conceptual model that is depicted in Figure 8 presents the information flow in the system.

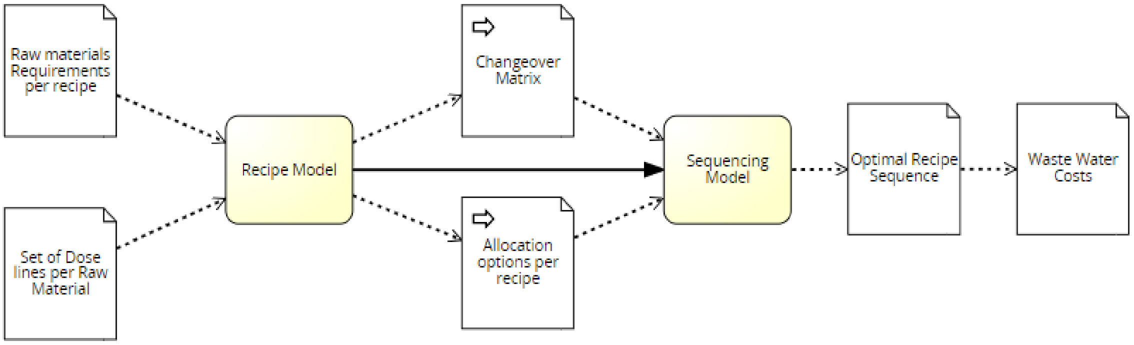


Figure 8 Information Flow Diagram

To better accommodate the process explained an example is given below. Let's assume that the objective is to define the optimal recipe sequence within family A. As depicted from Figure 8, the recipe model requires as an input 1) the raw material requirements per each recipe of family A and 2) the set of dose lines that the raw materials can be dosed. Based on this information, it is possible to completely enumerate the alternatives that each recipe generates given a selected set of dose lines. In this example, each recipe from family A generates 3 different combinations per recipe. Table 9 presents the complete list which is used as an input (Input 1) for Stage 2.

Table 9 Input 1 for Stage 2- Allocation per Combination List

Combinations	A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
AC5 1	0	5	0	0	0	0	4	12	11	6	0	16	0	0	27
AC5 2	0	5	0	0	0	0	4	12	11	6	0	16	0	27	0
AC5 3	0	5	0	0	0	0	4	12	11	6	0	16	27	0	0
AK5 4	0	5	0	0	0	0	4	12	11	6	0	0	0	27	14
AK5 5	0	5	0	0	0	0	4	12	11	6	0	0	27	0	14
AK5 6	0	5	0	0	0	0	4	12	11	6	0	27	0	0	14
AY5 7	0	5	0	0	0	0	4	12	11	6	0	0	20	0	27
AY5 8	0	5	0	0	0	0	4	12	11	6	0	0	20	27	0
AY5 9	0	5	0	0	0	0	4	12	11	6	0	27	20	0	0
AM5 10	0	5	0	0	0	0	4	12	11	6	0	0	0	18	27
AM5 11	0	5	0	0	0	0	4	12	11	6	0	0	27	18	0
AM5 12	0	5	0	0	0	0	4	12	11	6	0	27	0	18	0

Based on this list, it is possible to obtain the changeover matrix for family A. Since the 4 recipes result in 12 combinations, the changeover matrix will be a 12x12 matrix. The changeover matrix provides the number of changeovers occur when production switches for example from recipe AC5 1 to AM5 10. The changeover matrix of this family can be seen in Table 10. The process for obtaining both the recipe combination list and the changeover matrix is explained in detailed in the following Sections. Using these two inputs, it is possible to obtain an optimal recipe sequence for this family and subsequently use it to determine the waste water costs.

Table 10 Input 2 Changeover matrix for family A

	AC5 1	AC5 2	AC5 3	AK5 4	AK5 5	AK5 6	AY5 7	AY5 8	AY5 9	AM5 10	AM5 11	AM5 12
AC5 1	0	2	2	3	3	2	2	4	3	2	4	3
AC5 2	2	0	2	2	4	3	4	2	3	3	3	2
AC5 3	2	2	0	4	2	3	3	3	2	4	2	3
AK5 4	3	2	4	0	2	2	3	2	4	2	3	3
AK5 5	3	4	2	2	0	2	2	3	3	3	2	4
AK5 6	2	3	3	2	2	0	3	4	2	3	4	2
AY5 7	2	4	3	3	2	3	0	2	2	2	3	4
AY5 8	4	2	3	2	3	4	2	0	2	3	2	3
AY5 9	3	3	2	4	3	2	2	2	0	4	3	2
AM5 10	2	3	4	2	3	3	2	3	4	0	2	2
AM5 11	4	3	2	3	2	4	3	2	3	2	0	2
AM5 12	3	2	3	3	4	2	4	3	2	2	2	0

4.2 A two-stage approach

4.2.1 Stage 1: Recipe Model

This section explains how the recipe model was constructed to create the recipe input. Recipes needed to be expressed in a software friendly format to instantiate the entire process. Section 4.2.1.1 and Section 4.2.1.2 present the input requirements and the concept of recipe format adopted. Section 4.2.1.3 demonstrates the methodology followed to construct the recipe-combination list. This list was subsequently used for the calculation of all changeover matrices as explained in Section 4.2.1.4.

4.2.1.1 Input Requirements

The recipe model requires solely two input requirements. These are:

1. The raw materials that are used per recipe.
2. The set of dose lines that each raw material can use.

In the examined case, there are overall 22 recipes, 30 raw materials and 15 dose lines.

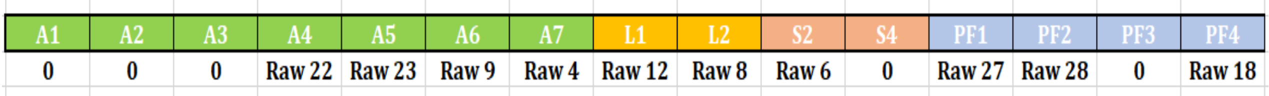
4.2.1.2 Recipe Formulation

To ensure the understanding of the process, an illustrative example is given coupled with the procedure analysis. The example concerns a recipe M7_K (Family M7, black ink). Confidentiality reasons don't allow revealing relevant information regarding the recipe structure. So, the actual raw materials are encrypted (e.g. Raw 27). *Figure 9* represents a feasible option to represent M7_K. given the ingredients and the set of dose lines provide in Table 11.

Table 11 Raw materials and dose lines requirements for M7_K recipe

M7_K	Dose Lines
RAW 4	A7
RAW 6	S2
RAW 8	L2
RAW 9	A6

RAW 12	**L1**
RAW 14	**PF4**
RAW 22	**A4**
RAW 23	**A5**
RAW 27	**A3**
RAW 28	**L2, PF1, PF2, PF3, PF4**
RAW 30	**L2, PF1, PF2, PF3, PF4**



A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
0	0	0	Raw 22	Raw 23	Raw 9	Raw 4	Raw 12	Raw 8	Raw 6	0	Raw 27	Raw 28	0	Raw 18

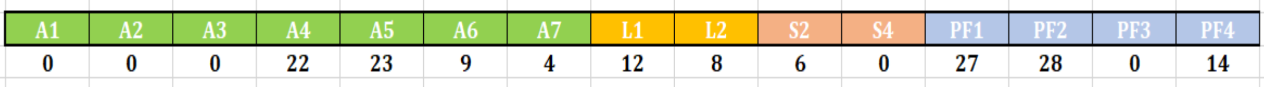
Figure 9 Initial Representation of Recipe M7_K

This representation was not a software friendly format. Hence, each recipe needed to have certain structured to be used as an input. The process includes **3 steps**:

Step 1: Substitute the name of raw materials with numbers. For example, Raw 22 was substituted by 22, Raw 23 was substituted by 23 as forth and so on. Since there are 30 raw materials the resulted raw material list ranges from 1 till 30.

Step 2: Substitute the set of dose lines with numbers. Dose lines list ranges from 1 to 15.

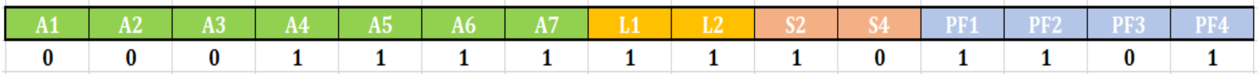
These actions have enabled the transformation of each recipe from a sequence of 15 blocks to a 15-digit code. Each digit position represents one specific dose line and the number represents the raw material that is dosed at a certain moment when a dose line is idle the block contains the value zero (0). Figure 10 depicts how M6_K was transformed after applying the 2 steps that previously mentioned.



A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
0	0	0	22	23	9	4	12	8	6	0	27	28	0	14

Figure 10 Digit representation of Recipe M7_K

Step 3: Express the number of raw materials in a binary (0-1) format. Value 0 represents an empty dose line whereas value 1 is used to represent a dose line loaded with a raw material. *Figure 11* depicts how recipe M6_K is finally expressed in binary format.



A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
0	0	0	1	1	1	1	1	1	1	0	1	1	0	1

Figure 11 *Binary representation of Recipe M7_K*

4.2.1.3 Recipe Combination List

Using this format made it was easier to continue with the generation of the Recipe Combination List. This list contains all possible allocations options that a single recipe can have in the system. The procedure explained below was built step by step. The software used to support this process was

MATLAB. Using the same example (M7_K recipe) and the information from Table 11, the process can be explained as follows:

First step taken was to identify the set of dedicated dose lines (hereafter, fixed lines) and the set of variable dose lines (hereafter, flex lines) for each recipe. Each recipe has a specific set of fixed and flex lines. Flex lines are defined as the dose lines which can be used by different raw materials. For example, RAW 28 and Raw 30 can be dosed in one of L2, PF1, PF2, PF3 or PF4 dose lines. The set of these lines that can use interchangeable by RAW 28 and RAW 30 are flex lines for M7_K. The actual number of flex lines, however, is less. After observing the recipe requirement, one can see that RAW8 can only be dosed in L2 and RAW14 in PF4. Given the restrictions imposed by RAW 8 and RAW 18, the initial number of flex lines is reduced from 5 to 3 (PF1, PF2 and PF3). Hence, the final set of flex lines is PF1, PF2 and PF3. The number of flexible lines is related with the number of possible representations of the recipe in the system. For example, the allocation decision of RAW 28 clearly impacts the allocation decision of RAW 30. If RAW 28 is dosed in PF1 this implies that RAW 30 can now be dosed in L2, PF2, PF3 or PF4. So, the flex lines are L2, PF1, PF2, PF3 and PF4.

On the contrary, fixed lines are the dose lines which are used for dosing specific raw material. For example, RAW 6 can only be dosed in dose line S2. Once the flex lines are identified, it is easy to derive the set of fixed lines for recipe M7_K. Therefore, the flex lines include A1, A2, A3, A4, A5, A6, A7, L1, L2, S2, S3 and PF4. Using this information, the complete set of dose lines (from 1 to 15) was split it into two parts (vectors); the fixed part and the flex part. Figure 12 depicts the splitting process.

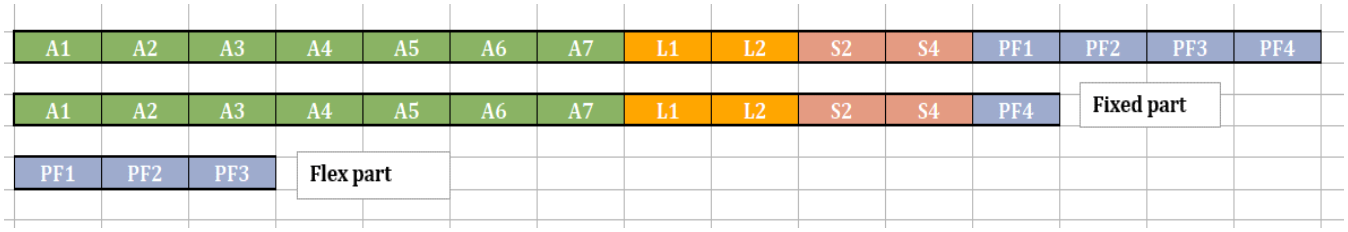


Figure 12 Dose lines splitting process

Then the flex part was used to estimate all the possible permutations using the P = perms(v) function in Matlab. Following this procedure recipe M7_K generates 6 different combinations.

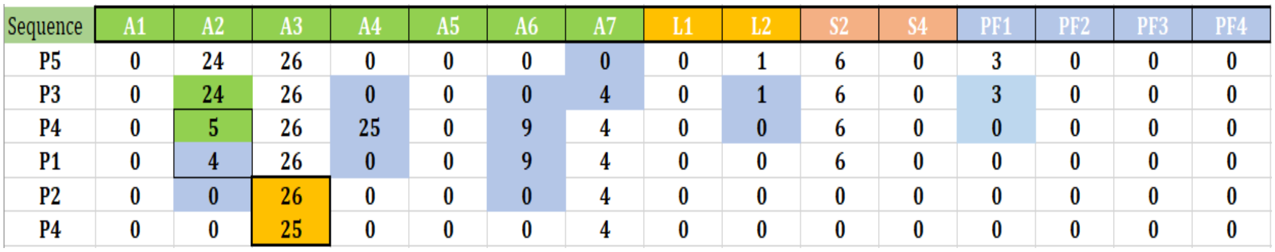
Table 12 Total number of combinations for recipe M7_K

A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
0	0	26	22	23	9	4	12	8	6	0	0	28	27	14
0	0	26	22	23	9	4	12	8	6	0	0	27	28	14
0	0	26	22	23	9	4	12	8	6	0	28	0	27	14
0	0	26	22	23	9	4	12	8	6	0	28	27	0	14
0	0	26	22	23	9	4	12	8	6	0	27	0	28	14
0	0	26	22	23	9	4	12	8	6	0	27	28	0	14

This procedure followed for each of 22 recipes that exist in the system. The total number of combinations generated account to **203**. There are recipes that can only represented by one combination (i.e. M6_K) but also there are recipes that can be presented by as many as 36 combinations (i.e. P_6).

4.2.1.4 Changeover Matrix

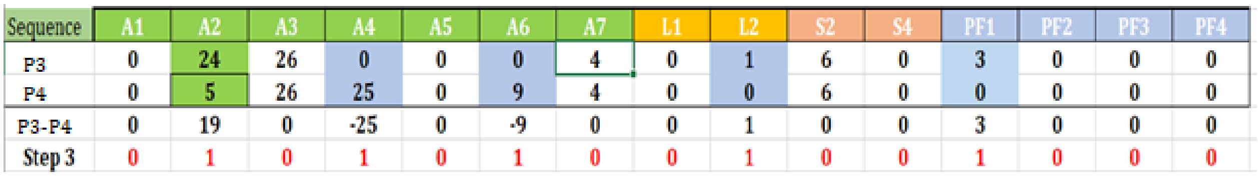
The changeover matrix is the key input for the Sequencing Model next. As mentioned, a changeover occurs in the system when two consecutive recipes require the same dose line, but a different raw material needs to be dosed. To calculate the changeover matrix, it is necessary to use the recipe-combination list as resulted from Section 4.2.1.3. Let's assume a possible production sequence within the Family P.



Sequence	A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
P5	0	24	26	0	0	0	0	0	1	6	0	3	0	0	0
P3	0	24	26	0	0	0	4	0	1	6	0	3	0	0	0
P4	0	5	26	25	0	9	4	0	0	6	0	0	0	0	0
P1	0	4	26	0	0	9	4	0	0	6	0	0	0	0	0
P2	0	0	26	0	0	0	4	0	0	0	0	0	0	0	0
P4	0	0	25	0	0	0	4	0	0	0	0	0	0	0	0

Figure 13 Recipe Sequence of Family P

This sequence creates 11 changeovers depicted in distinct colors. For instance, P3 and P4 both require dose line A2 but different raw material needs to be dosed (24 instead of 5). The required changeovers needed by moving from recipe P3 to P3 can simply be found by subtracting these two recipes cell by cell. When a cell contains a non-zero value, indicates that a changeover happened. But since the value can be anything (positive or non-positive), Step 3 is applied. This step is essential because the total number of changeovers can now be calculated by summing up the cells that have value one. If this format was adopted before the estimation would not be possible since value 1 represents the existence and not the content of the raw material. Thus, the total number of changeovers from switching production from P3 to P4 is 5 (=0+1+0+1+0+1+0+0+1+0+0+1+0+0+0). Figure 14 presents analytically the procedure as explained.



Sequence	A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
P3	0	24	26	0	0	0	4	0	1	6	0	3	0	0	0
P4	0	5	26	25	0	9	4	0	0	6	0	0	0	0	0
P3-P4	0	19	0	-25	0	-9	0	0	1	0	0	3	0	0	0
Step 3	0	1	0	1	0	1	0	0	1	0	0	1	0	0	0

Figure 14 Example of calculating changeovers

The same methodology applied to estimate the changeover matrix for the entire recipe-combination list. The dimensions of changeover matrices depends on the number of combinations that a data set of the initial recipes generate. For instance, the entire data set (22 recipes) generates 203 combinations, so the dimensions of the changeover will be 203x203. For the given example of 6 specific recipes the changeover matrix can be shown in Table 13.

Table 13 Changeover Matrix for Family P

	P5	P3	P4	P1	P2	P4
P5	0	1	6	5	5	6
P3	1	0	5	4	4	5
P4	6	5	0	2	4	5
P1	5	4	2	0	3	4
P2	5	4	4	3	0	1
P4	6	5	5	4	1	0

4.2.2 Stage 2: The Sequencing Model

In the examined setting, a Mixed Integer Linear Programming Model (MILP) was developed to solve the sequencing problem for all recipes. As seen in the literature review, production scheduling with sequence-dependent set-up cost is a challenging problem. A solution to optimality can be difficult due to the NP-hard nature of most of these problems. The solution time depends on the size of the problem and the computing technologies. These factors discouraged the deployment of mathematical models as primary approach to obtain optimal solutions.

4.2.2.1 Model Assumptions

To set the starting point of the model it is necessary to provide a list of certain assumptions for the MILP model. These assumptions are made after analyzing the current system and identifying its limitations. The main assumptions are grouped into 4 distinct categories according to their relevance. The assumptions are defined as follows:

General

- The number of recipes is fixed and known (22 recipes).
- The raw materials per recipe are fixed and known. The requirements of each recipe in terms of raw materials is fixed. Any future modification regarding the recipe formula is not considered.
- Demand is considered constant, continuous, evenly spread among the recipes and known. Demand forecasting is beyond the scope of this paper. Logistics department is responsible for applying the right strategy to forecast the demand. According to their records, demand does not fluctuate much between different ink products and does not follow any seasonality pattern. Thus, these observations justify the corresponding assumption.
- Production is made in batches and each batch represents a single recipe. Ink is recipe-based product and each batch is a specific mix of raw materials according to the recipe instructions. Mixing recipes is not possible.
- The time horizon modelled is a week. As mentioned, Océ wishes to apply EPEW production principle. So, the corresponding production sequence refers to a weekly production schedule.
- Every recipe produced once. The EPEW production principle is associated with the repetitively application of a cyclic production schedule. So, in such a schedule a recipe is produced once.

- For each product one batch will be produced in a period. Given the EPEW policy, production is made in small and frequent batches. So, a single batch production is the minimum quantity that currently can be produced following the policy's requirements.

Resources

- The only resources in terms of equipment considered are the available number of dose lines. Capacity difference in any other aspect (such as vessels capacity) will not affect the decisions regarding the product sequence.
- The set of dose lines that each material uses is fixed and known. Given the recipe ingredients, the set of permittable dose lines per raw material is defined by the Research and Development department and the Equipment Engineers. The sets were defined following the characteristics and technical requirements of each raw material.
- The amount of raw materials is sufficient to produce each recipe for the given horizon. Procurement department is responsible to ensure the raw material availability. Procurement or Supply Chain activities are beyond the scope of this paper. Thus, these observations justify the corresponding assumption.
- The production rate per recipe is the same which leads to a constant production time per recipe (deterministic processing time). The processing time per recipe does not varies substantially among recipes and does not include stochasticity (for instance, there is not maturation time like in the dairy industry). This justifies the assumption regarding the determinist processing times.

Changeovers

- A changeover occurs when two consecutive recipes use the same dose line but have different raw material needs.
- The system begins with empty dose lines. So, no changeovers required to initiate the production. In real life, the initial state is determined by the configuration of the last recipe produced. For example, if the last recipe produced is recipe A_C then the dose lines are dosed with the materials of that recipe. However, the changeover matrix was calculated under this assumption. The initial state is reflected as a dummy variable with zeros as raw materials.
- The system considers as changeover the transition from an empty state to a raw material and the transition from a raw material to an empty state. In real world, the dose lines are not flushed if the next recipe does not use the same dose line. So, the dose material never returns to an empty state.

The last two assumptions result in overestimating the number of changeovers. The actual changeovers can be found manually once the final sequence is obtained. Then the size of the problem decreases substantially (especially in family level analysis) and the actual number of changeovers are noticeable.

Cleaning

- Cleaning is only associated with the cleaning of dose lines. This cleaning of dose lines reflects the variable waste water cost component. The recipe sequence and the decision of raw material allocation result in different waste cost. Thus, the cost in the dose lines is sequence dependent.
- The cleaning of the vessel and filling and packaging line generate a fixed amount of water which is associated with the fixed cost component. The cleaning of the rest equipment such as vessel occurs always and results in specific waste water cost independently the recipe. Thus, it is sequence independent. As a result, the focus is set on the dose lines.
- Cleaning duration per recipe is fixed and known.
- Minor and major set ups were treated equally.

4.2.2.2 Nomenclature

4.2.2.2.1 Sets

I	Set of Recipes $= \{1, \ldots, 22\}$
J	Set of entire Combinations $= \{1, \ldots, 203\}$

4.2.2.2.2 Indices

i , k	Recipes
j , l	Combinations

4.2.2.2.3 Parameters

C_{jl}	Number of changeovers occur when switching from combination *j* to *l*
Z_{ij}	1 if recipe *i* is allowed to have combination *j*; 0, otherwise

4.2.2.2.4 Binary Variables

X_{ij}	=1 if recipe *i* uses combination *j*; 0, otherwise
Y_{ijkl}	=1 if recipe *i* with combination *j* is followed by recipe *k* with combination *l* *where i≠k and j≠l*; 0, otherwise
G_{ik}	if recipe *i* is followed by recipe *k where i≠k;* 0, otherwise

4.2.2.2.5 Integer Variables

U_i	variable which illustrates the sequence of recipe *i*

4.2.2.3 Model Formulation

Objective: $$Min \sum_{i,k \in I} \sum_{j,l \in J} Y_{ijkl} C_{jl} \qquad (1)$$

Subject to

$$\sum_{j,\in J} X_{ij} = 1 \qquad \forall i \in I \qquad (2)$$

$$X_{ij} \leq Z_{ij} \qquad \forall i \in I\ , j \in J \qquad (3)$$

$$X_{ij} = \sum_{k\in I} \sum_{l\in J} Y_{ijkl} \qquad \forall i \in I\ , j \in J \qquad (4)$$

$$X_{ij} = \sum_{k\in I} \sum_{l\,\in J} Y_{klij} \qquad \forall i \in I\ , j \in J \qquad (5)$$

$$Y_{ijij} = 0 \qquad \forall i \in I\ , j \in J \qquad (6)$$

$$Y_{ijkl} + Y_{klij} \leq 1 \qquad \forall i, k \in I\ , j, l \in J \qquad (7)$$

$$G_{ik} = \sum_{j,l\in J} Y_{ijkl} \qquad \forall i, k \in I\ , j, l \in J \qquad (8)$$

$$U_i - U_k + n\, G_{ik} \leq n - 1 \qquad \forall i \neq k\ \in I/\{1\} \qquad (9)$$

$$2 \leq U_i \leq n \qquad (10)$$

$$U_1 = 1 \qquad (11)$$

$$Y_{ijkl}\,, X_{ij}\ \in \{0,1\} \qquad \forall i, k \in I\ , j, l \in J \qquad (12)$$

The purpose of the proposed MILP is to find an optimal or feasible production sequence for the pilot plant given the manufacturing restrictions. Therefore, objective function (1) was formulated to minimize the total number of changeovers given the selected recipe-combination.

The first two constraints ensure sequence feasibility. *Constraint 2* guarantees that each recipe is assigned to only one combination and *Constraint 3* ensures that each recipe will be assigned only to valid combinations.

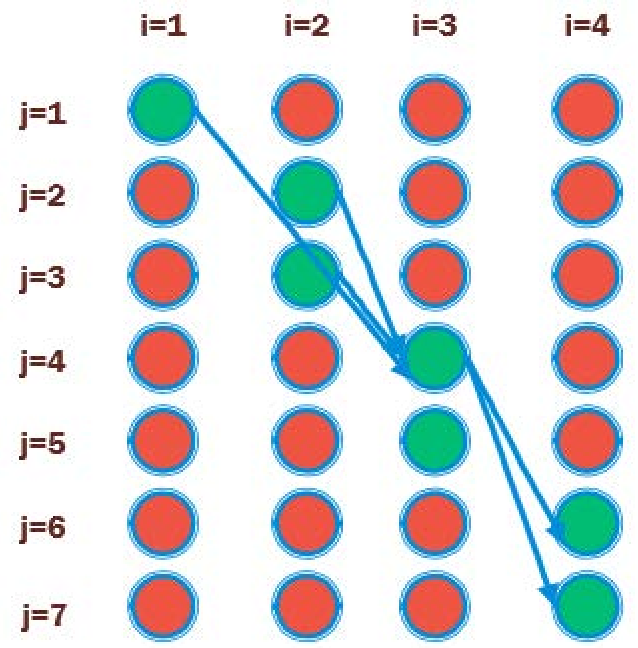


Figure 15 Recipe Node Network

A recipe-combination can be as a node network as presented in Figure 15. In such a network, *Constraint 4* guarantees that from a recipe *i* with combination *j* there is only one out coming arc to a recipe *k* with combination *l*. *Constraints 5* guarantees that the summation of incoming arcs from all recipe k with combination l to recipe *i* with combination *j* must be one. These are known as balance constraints. However, it was necessary to add *Constrains 6* and *7* to avoid two cases which satisfy the balance constrains but are not valid.

Based on this observation, the balance constraints basically ensure for instance that node (1,4) must have only one incoming arc and one out coming arc. But these contrains do not protect the system from having the situations decpicted in Figure 16. So, *Constrains 6* and *7* ensure the elimination of these incedents.

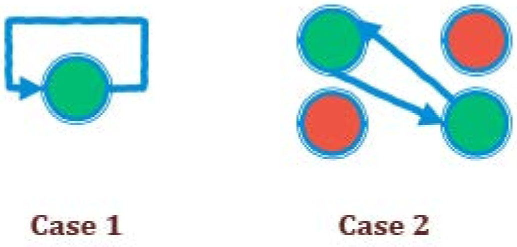


Figure 16 Exception Handling

Constraints (8-11) are the classical subtour elimination constraints proposed by the Miller, Tucker and Zemlin (hereafter, MTZ) to avoid unusable solutions that contain subtours (Miller et al, 1960). The subtours in the context of the recipe problem can be shown in the example depicted in Figure 17. In this case, instead of a single recipe sequence that is desired, two recipe loops *(i1, i*2*, i*3*, i*4, *i*1*)* and *(i*5*, i*6*, i*7, *i*5*)* are generated. Although this solution satisfies *Constraints 4 to 7*, it does not satisfy *Constraint 9*. Finally, *Constraint 12* is the integrality constraint.

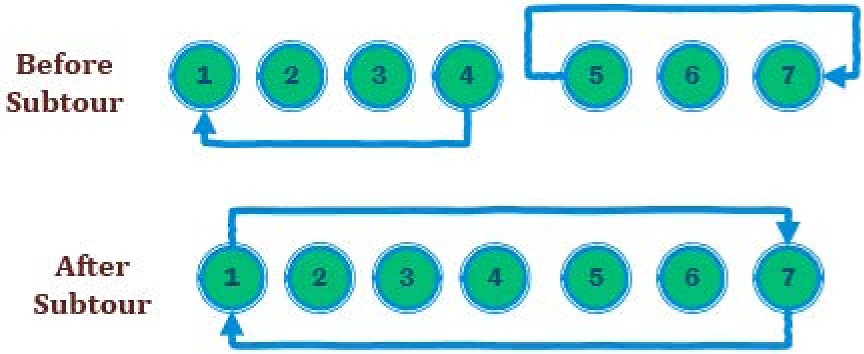


Figure 17 Example of Subtour Elimination

4.2.2.4 Implications

Using mathematical methods to support the joint optimization of recipe sequencing and raw material allocation has many advantages. Unfortunately, the scheduling problem for substantial number of recipes, thus, combinations is intractable for optimization models alone. MILP shares similarity to the Travel Salesman Problem (TSP) which belongs to the NP-complete problems. Thus, it can be shown easily that is an NP-hard problem.

In the specific setting, the recipe number including all possible combinations increases from 22 to 203. Therefore, it is highly likely a commercial solver not to be able to handle the entire data set either in a reasonable computational time or at all. However, an attempt was made to solve the full sample on a 2.5 GHz CPU (utilizing 1 core and 1 thread) with 16.00 GB RAM, using the proposed model for the entire data set. Unfortunately, it was not possible. Hence, the MILP model (exact method) can be applied for a certain number of recipe-combinations.

This implication motivated the decomposition of the sequencing model adopting different strategies to decrease complexity. The different strategies use both exact and heuristic algorithms. Section 5 provides a detailed analysis of the strategies developed.

5 Decomposition of Sequencing Model

This section presents the different strategies developed to approach the NP-hard nature of the problem. The concept of decomposition is an old idea that is used for solving large-scale linear problems from the 1960s (Dantzig and Wolfe, 1960). In this context, the sequencing problem was decomposed in two steps.

The first step concerns the partitioning of the initial data set (203 recipe-combinations list) into smaller data sets. The decisions regarding this step basically indicate the level in which the recipe sequence is obtained. The next step provides different techniques for the linking of the new data sets created in step 1 into one to obtain an integral cycle production schedule including all recipes. Both steps use a mix of exact and heuristic algorithms. The advantage of this method lies in fact that a recipe sequence is acquired step by step and the problem's complexity is gradually decreased.

5.1 Step 1: Data Set Partitioning

The decision regarding the splitting of the data set lies mostly in the preference of the end user. In this context, two approaches were introduced to split the data. The first approach splits the data according to the family concept and the second approach regarding the arbitrary groups. Once the decision is made, the MILP model is applied to obtain the optimal recipe sequence in the corresponding level. So, the resulted recipe sequence from the first step would be in a *Family Level* as opposed to the second which will be in *Group Level*.

5.1.1 Approach 1: Family Level

In the examined setting there are 5 different families (Fam A, Fam CL, Fam M6, Fam M7 and Fam P). The number of recipes of families can vary but their size is manageable for the MILP model. Therefore, it can be used to obtain the sequence which minimizes the number of changeovers in a family level. The completion of this step generates 5 different recipe sequences as seen in Figure 18.

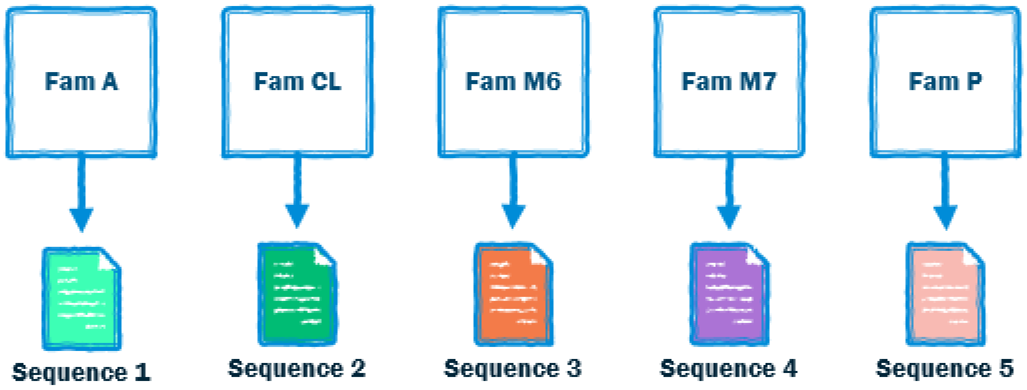


Figure 18 Result after sequencing recipes within a family

5.1.2 Approach 2: Group Level

In this step, diverse groups can be created including different recipes. The size of the group formulated, however, cannot be very large due to capacity memory problems. In this context, the entire data set was split into two groups. Group 1 includes Family A, Family CL, Family M6, and

Family M7 and Group 2 is basically Family P. The group formulation decision was made after observing the system characteristics and applying two rules:

1. The first rule applied concerns the demand. The demand for inks (Group 1) is constantly higher as compared to the demand of primers (Group 2). So, grouping all ink families together will result in sequencing products with higher priority.
2. The second rule applied is regarding the computational complexity. From modeling point of view the 6 recipes of Fam P generate 79 combinations which account roughly to 40% of entire systems combinations.

Therefore, considering the exponential solution time (*NP hard* problem) and the priority of each group, the recipe sample was split unequal in a rational way. The completion of this step will generate 2 different recipe sequences.

5.2 Step 2: Linking the Data sets

Once Step 1 is complete all families should be linked to obtain an overall sequence. In general, the linking of the groups/families can be done in two ways; static and dynamic. The decision is made based on the number of family blocks/groups to be connected.

Static linking is preferable when the number of block/groups are more than two. This technique enables the linking of the family blocks solely based on the indications of the first and last recipe of each family block. Once the block/group sequence is defined, no further optimization steps applied within the family. In this report, the static linking concept is covered by the deployment of two exact methods and one heuristic. Section 5.2.1 presents the family linking using the classical model of the Travel Salesman Problem (TSP) in a family/group level. Finally, Section 5.2.3 provides the developed heuristic which arises from the Group Technology Concept.

A ***dynamic linking*** approach can be applied when the size of families/ groups equals to two. In a dynamic linking the sequence of one block (as resulted after using MILP to find the optimal in the examined set) is fixed whereas the recipe sequence of the next block is optimized based on the last recipe for the first block that is used as a reference point to connect the families. Dynamic linking method has the advantage of selecting the sequence of the second block/group from scratch using as a reference the last recipe from the previous block. This leads to more robust recipe-combination decisions. Dynamic linking requires a two stage MILP based approach.

Figure 19 represents how the aforementioned concepts applied to link Family A and Family CL using. Following the static linking method, families are connected based on recipes A_Y and CL_K1. Observe that after connecting the families the sequence of Family P is the same with the one obtained when MILP was applied in a family level.

When the dynamic linking concept is used, linking is done using A_Y and the complete list of all allocation per recipe from Family P. As a result, a new recipe sequence is obtained which is exactly adjusted to A_Y. As can be seen in Figure 19, the dynamic linking results to a new sequence where recipes are ordered differently and additionally, they carry a different allocation option.

Figure 19 Static vs Dynamic Linking

5.2.1 Exact Method: TSP based approach for family blocks/group sequencing

A scientific approach to link the families is using the Travel Salesman Problem (TSP). TSP is also an NP-complete problem, but it has been extensively studied and used in the literature to solve similar cases. The TSP model uses as an input the 5 different recipe sequences as resulted from Approach 1. The input is modified to be valid for the TSP model. Next sections explain the procedure followed.

5.2.1.1 Input Generation

In this concept families are seen as blocks and aim is to find the sequence of these blocks. Each block carries its own optimized sequence after applying the MILP model within the family. The first and the last recipe of each block are used as reference points to link the blocks (see Figure 20).

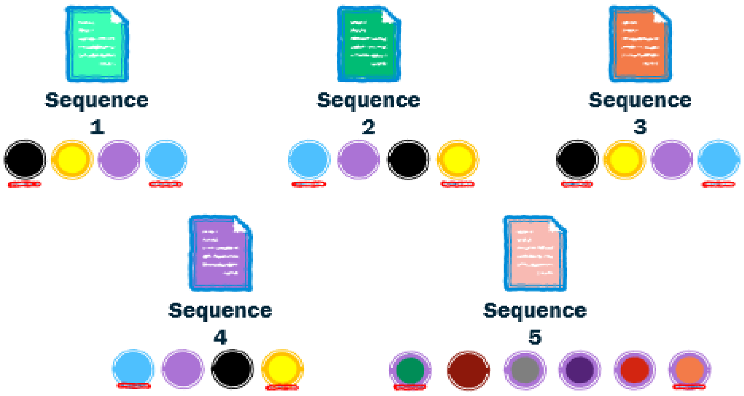


Figure 20 Recipe Sequence per Family Block

Hence, each family can be seen only as a two-instant component in the solution space (see Figure 21). Considering that each family block is now represented only by two recipes, the solution searching space is substantially decreased. This enables the linking of many family blocks, thus the linking of many recipes.

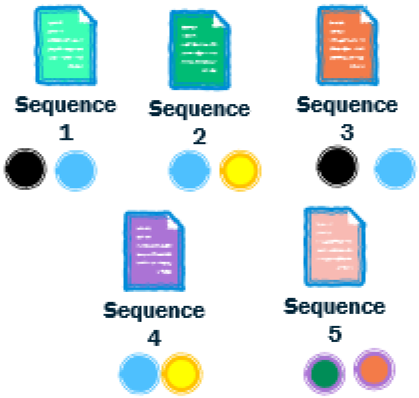


Figure 21 New Family Representation - TSP input

5.2.2 Nomenclature

5.2.2.1 Sets

I	Set of Recipes = $\{1, \dots, 8\}$

5.2.2.2 Indexes

i, k	Recipes

5.2.2.3 Parameters

C_{ik}	Number of changeovers that occur when switching from recipe *i* to *k*

5.2.2.4 Binary Variables

W_{ik}	=1 if goes from recipe *i* to recipe k; 0, otherwise

5.2.2.5 Integer variables

U_i	variable which illustrates the sequence of recipe *i*

5.2.2.6 Model Formulation

Objective: $$Min \sum_{i,k \in I} W_{ik} C_{ik} \qquad (13)$$

Subject to

$$\sum_{k \in I} W_{ki} = 1 \qquad \forall i, i \neq k \in I \qquad (14)$$

$$\sum_{k\in I} W_{ik} = 1 \qquad \forall i, i \neq k \in I \qquad (15)$$

$$U_i - U_k + nW_{ik} \leq n - 1 \qquad \forall i \neq k \ \in I/\{1\} \qquad (16)$$

$$2 \leq U_k \leq n \qquad (17)$$

$$U_1 = 1 \qquad (18)$$

$$W_{ik} \ \in \{0,1\} \qquad \forall i, k \in I \qquad (19)$$

Recall that, the ultimate objective of the optimization problem is to minimize the number of changeover. In this case there is no need to select recipe combination. *Constrain 14* guarantees that each recipe *i* will be visited once and *Constrain 15* ensures that there is exactly one departure from each recipe *i* to other recipe *j*. *Constrains 16* to *18* regard are the MTZ subtour elimination constrains.

5.2.3 Heuristic approach: Group Technology Approach for family blocks sequencing

The Group Technology Concept is a widely applied method in the manufacturing industry. The Group technology concept suggests that processes or parts with high similarity should be processed together (Gupta & Chantaravarapan, 2008). So, it is frequently used to reduce setup costs, work-in-process inventory costs, lead times, and material handling costs. Basically, the recipe families are formulated using this concept; recipes with high similarity formulate a family.

Thinking this concept in a higher level, families with high similarity should also be processed together. The conception of the idea motivated the development of a methodology to link the families. The aim was to provide a heuristic which guideline the linking of high congruent families.

5.2.3.1 Methodology

- The analysis starts by identifying what are the raw material needs for each family. Table 14 presents the aggregated requirements in raw materials per family.

Table 14 Aggregated requirements in raw materials per family

Raws	**Fam A**	**Fam CL**	**Fam M6**	**Fam M7**	**Fam P**
Total:	**14**	**14**	**12**	**14**	**10**

- The family congruency is assessed based on the amount common raw materials. The results are shown in the symmetric matrix below (Table 15).

Table 15 Common Raw Materials between Families

	Fam A	Fam CL	Fam M6	Fam M7	Fam P
Fam A	🟥	8	8	10	4
Fam CL		🟥	3	5	3
Fam M6			🟥	11	4
Fam M7				🟥	3
Fam P					🟥

- Using the results obtained from the previous steps (Table 14 and Table 15), the congruency between families is expressed in percentages and the overall results are summarized in Table 16.

Table 16 Congruency in terms of Percentages

	Fam A	Fam CL	Fam M6	Fam M7	Fam P
Fam A	🟥	40%	44%	56%	20%
Fam CL		🟥	13%	22%	15%
Fam M6			🟥	73%	22%
Fam M7				🟥	15%
Fam P					🟥

Three scenarios are identified for linking the family blocks using Table 16. These are:

Scenario 2a: Fam M6→ Fam M7 → Fam A → Fam CL → Fam P

Scenario 2b: Fam M7→ Fam M6 → Fam A → Fam CL → Fam P

Scenario 2c: Fam M6→ Fam M7 → Fam A → Fam P → Fam CL

Figure 22 depicts the 3 scenarios (Scenario 2a, 2b and 2c) according to the Family Congruence percentage index generated.

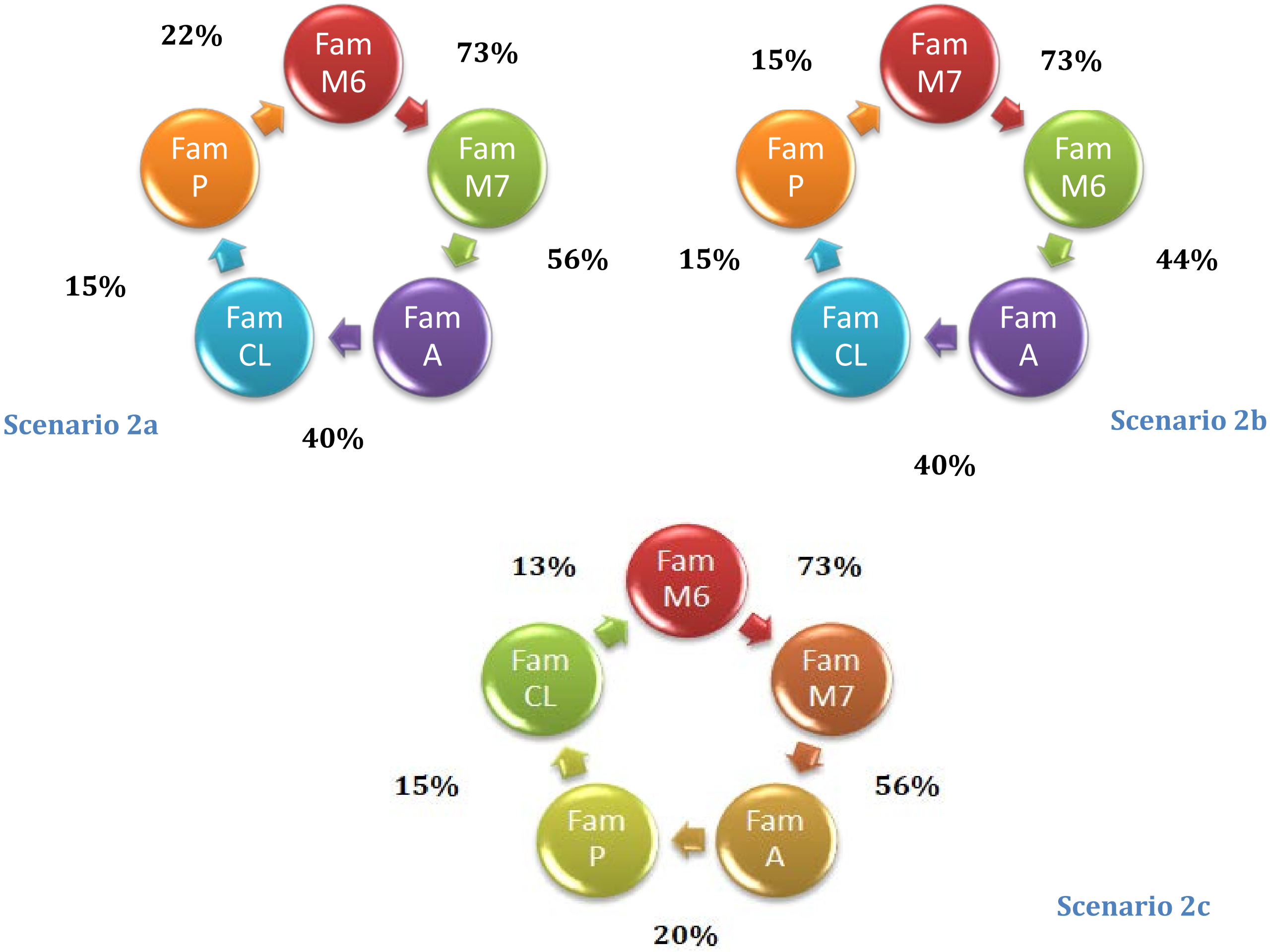


Figure 22 Scenarios under investigation for Group Technology Concept.

6 Computational Results

In this section, the numerical results of the strategies proposed in the previous section are discussed. All instances are solved on a 2.2 GHz CPU with 4.00 GB RAM using Java interface and Gurobi solver 6.5.2. The instances are run for a maximum time of 6 hours. The computational times are presented aiming to analyze the benefits of using the decomposition approach.

Section 6.1 provides an overview of the scenarios reviewed. Section 6.2 and Section 6.3 present the numerical results after applying the two-stage approach as explained in Sections 4.2.1 and Section 4.2.2 respectively. Finally, the results from the proposed strategies are compared and presented in Section 6.4.

6.1 Scenarios

The sequencing model decomposition leads to the development of different strategies to solve the sequencing problem. The efficiency of each strategy will be tested through the development of alternative scenarios. Figure 23 serves as a roadmap to explain the proposed strategies.

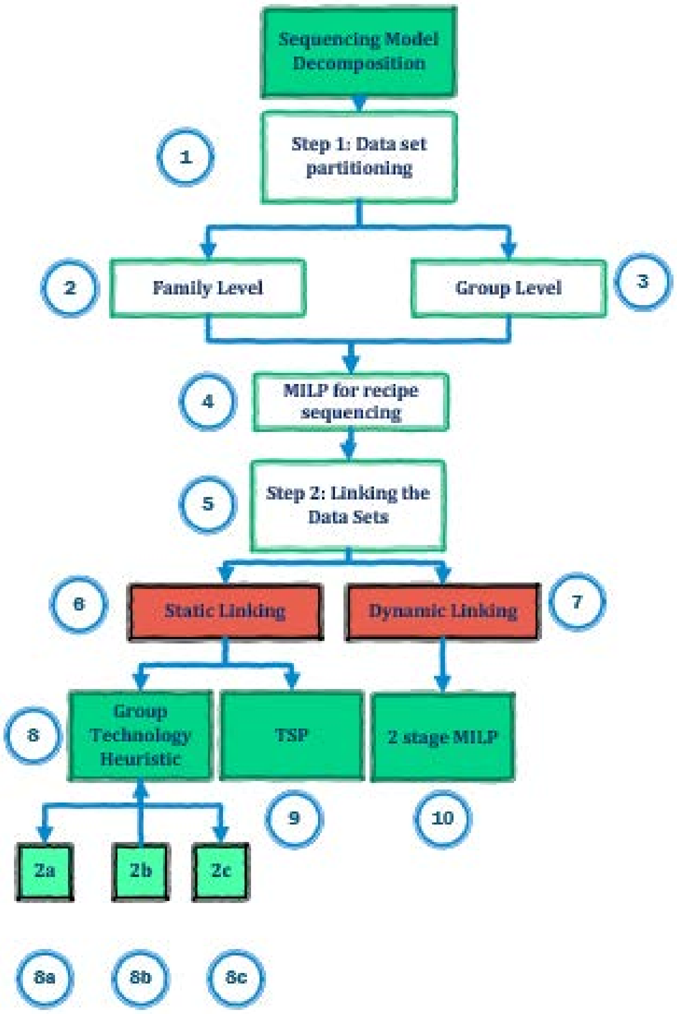


Figure 23 Methodologies Overview

The scenarios that can be investigated under the proposed strategies are:

Scenario 1: Data partitioning in a Family Level and static linking of family blocks using TSP (following the path 1-2-4-5-6-9).

Scenario 2: Data partitioning in a Family Level and static linking of family blocks using Group Technology Heuristic (following the path 1-2-4-5-6-8). This scenario results in 3 different sub-scenarios:

> ***Scenario 2a***: Data partitioning in a Family and static linking of family blocks using Group Technology Heuristic and Scenario 2a (following the path 1-2-4-5-6-8a)
>
> ***Scenario 2b***: Data partitioning in a Family Level and static linking of family blocks using Group Technology Heuristic and Scenario 2b (following the path 1-2-4-5-6-8b)
>
> ***Scenario 2c:*** Data partitioning in a Family Level and static linking of family blocks using Group Technology Heuristic and Scenario 2c (following the path 1-3-4-5-6-8c)

Scenario 3: Data partitioning in a Group Level and dynamic linking of recipes using 2 stage MILP model (following the path 1-3-4-5-7-10).

The proposed scenarios are developed using mixing and matching techniques regarding splitting and linking the different data sets. Since, all scenarios share common numerical results this section is structured following the decomposition steps. The implementation of each step provides information regarding the recipe sequences, the number of changeovers, the computational time and the waste water costs.

6.2 Results after applying Step 1

As mentioned, Step 1 concerns the partitioning of the initial data set into family level or group level. The decisions regarding the level of partitioning influence the obtained recipe sequence. Section 6.3.2 provides the results when data set is split in a family level and Section 6.3.1 when the data set is split in a group level.

6.2.1 Family Level

After applying the MILP model in a family level, 5 recipe sequences were generated. Table 17-Table 21 give an overview of the resulted sequences along with the of raw material allocation in the dose lines per recipe. The combination selected appears as a number next to each recipe code. Finally, Table 22 summarizes the results per family and provides additional information regarding the number of changeovers, the computational time and the waste water costs.

Table 17 Recipe Sequence with Family A

Fam A	A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
A_K _6	0	5	0	0	0	0	4	12	11	6	0	0	27	0	14
A_C_4	0	5	0	0	0	0	4	12	11	6	0	16	27	0	0
A_M_12	0	5	0	0	0	0	4	12	11	6	0	0	27	18	0
A_Y_9	0	5	0	0	0	0	4	12	11	6	0	0	20	27	0

Table 18 Recipe Sequence with Family C

Fam C	A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
C_K_68	0	5	26	0	0	30	4	13	0	6	7	0	0	28	15
C_M_26	0	5	26	0	0	30	4	13	0	6	7	0	0	19	27
C_C_47	0	5	26	0	0	30	4	13	0	6	7	17	0	0	27
C_Y_5	0	5	26	0	0	30	4	13	0	6	0	0	21	0	27

Table 19 Recipe Sequence with Family M6

Fam M6	A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
M6_C_2	0	0	26	22	23	9	4	12	8	6	0	16	0	0	0
M6_Y_3	0	0	26	22	23	9	4	12	8	6	0	0	20	0	0
M6_K_4	0	0	26	22	23	9	4	12	8	6	0	0	0	0	14
M6_M_5	0	0	26	22	23	9	4	12	8	6	0	0	0	18	0

Table 20 Recipe Sequence with Family M7

Fam M7	A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
M7_C_12	0	0	0	22	23	9	4	12	8	6	0	16	27	0	29
M7_Y_24	0	0	0	22	23	9	4	12	8	6	0	27	21	0	29
M7_K_ 7	0	0	0	22	23	9	4	12	8	6	0	27	29	0	14
M7_M_19	0	0	0	22	23	9	4	12	8	6	0	27	29	18	0

Table 21 Recipe Sequence with Family P

Fam P	A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
P6_76	0	24	26	0	0	0	0	0	1	6	0	3	0	0	0
P5_10	0	24	26	0	0	0	4	0	1	6	0	3	0	0	0
P3_5	0	5	26	25	0	9	4	0	0	6	0	0	0	0	0
P1_2	0	0	26	0	0	9	4	0	0	6	0	0	0	0	0
P2_3	0	0	26	0	0	0	4	0	0	0	0	0	0	0	0
P4_10	0	0	25	0	0	0	4	0	0	0	0	0	0	0	0

Table 22 Sequencing Results in a Family Level

Family	Sequence	Estimated Chgv.	Actual Chgv.	Waste [kg]	Waste Cost [€]	Time [ms]
Fam A	A_K _6 → A_C_4 → A_M_12 → A_Y_9	6	2	350	168	205
Fam C	*C_K_68 → C_M_26 → C_C_47 → C_Y_5*	7	5	740	290.5	10953
Fam M6	*M6_C_2 → M6_Y_3 → M6_K_4 → M6_M_5*	6	0	0	0	989
Fam M7	*M7_C_12 → M7_Y_24 → M7_K_ 7 → M7_M_19*	6	4	700	336	1898
Fam P	*P6_76 → P5_10 → P3_5 → P1_2 → P2_3 → P4_10*	12	2	230	56	11323

As stated in Section 4.2.2.1 the number of changeovers is overestimated. This requires an additional manual step to calibrate the resulted changeovers. Since the number of recipes per family level is small (4 or 6), the number of actual changeovers is presented in 4th column. The 5th and 6th column represent the calculated waste volume and corresponding cost respectively. The waste cost as mentioned represent the variable cost and depends on the changeovers that take place in the dose lines. Last column, presents the computational time for the results sequences.

6.2.2 Group Level

Recall that in this case the data set was split into two groups. Group 1 includes only the ink recipes whereas Group 2 only primers. The sequence obtained using the MILP model for Group 1 is shown in Table 23 and for Group 2 in Table 24 (same as Table 21). Table 25 summarizes the results in a group level.

Table 23 Recipe Sequencing Results for Group 1

Group 1	A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
M6_Y_99	0	0	26	22	23	9	4	12	8	6	0	0	20	0	0
M6_M_101	0	0	26	22	23	9	4	12	8	6	0	0	0	18	0
M6_K_100	0	0	26	22	23	9	4	12	8	6	0	0	0	0	14
M6_C_98	0	0	26	22	23	9	4	12	8	6	0	16	0	0	0
M7_C_108	0	0	26	22	23	9	4	12	8	6	0	16	0	28	27
M7_Y_ 120	0	0	26	22	23	9	4	12	8	6	0	0	21	28	27
M7_K_103	0	0	26	22	23	9	4	12	8	6	0	0	27	28	14
M7_M_115	0	0	26	22	23	9	4	12	8	6	0	0	27	18	28
A_M_ 12	0	5	0	0	0	0	4	12	11	6	0	0	27	18	0
A_C_ 4	0	5	0	0	0	0	4	12	11	6	0	16	27	0	0
A_K_6	0	5	0	0	0	0	4	12	11	6	0	0	27	0	14
A_Y_8	0	5	0	0	0	0	4	12	11	6	0	0	20	0	27
CL_Y_21	0	5	26	0	30	0	4	0	13	6	0	0	21	0	27
CL_C_ 63	0	5	26	0	30	0	4	0	13	6	7	17	0	0	27
CL_M_ 42	0	5	26	0	30	0	4	0	13	6	7	0	0	19	27
CL_K_ 84	0	5	26	0	30	0	4	0	13	6	7	0	0	28	15

Table 24 Recipe Sequencing Results for Group 2 under Dynamic Linking

Group 2	A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
P6_76	0	24	26	0	0	0	0	0	1	6	0	3	0	0	0
P5_10	0	24	26	0	0	0	4	0	1	6	0	3	0	0	0
P3_5	0	5	26	25	0	9	4	0	0	6	0	0	0	0	0
P1_2	0	0	26	0	0	9	4	0	0	6	0	0	0	0	0
P2_3	0	0	26	0	0	0	4	0	0	0	0	0	0	0	0
P4_10	0	0	25	0	0	0	4	0	0	0	0	0	0	0	0

Table 25 Sequencing Results in a Group Level

Groups	Sequence	Estimated Chgv.	Actual Chgv.	Waste [kg]	Cost [€]	Time
Group 1	**M6→ M7→ A→CL**	38	15	2645	1113	376[min]
Group 2	**P**	12	2	230	56	11323 [ms]

Comparing the results obtained when sequencing in a Family level (Table 17-Table 20) and Group level (Table 23) (excluding Family P) 2 things can be observed: first, the sequence of recipes is different among those two levels and additionally, the selected allocation per recipe is also different.

In addition, the recipe sequence of Group 1 is of great interest. Recall that Group 1 is formed by adding the recipes of 4 ink families arbitrary in a file. The proposed sequence justifies the concept of family by placing the recipes which belong to the same family eventually next to each other.

6.3 Results after applying Step 2

The sequencing of the family blocks can be accomplished using two (static) approaches; Group Technology Heuristic developed and the TSP model. Group Technology Heuristic provides 3 different linking scenarios according to the family congruency whereas the TSP model investigates the optimal linking of the family blocks. Additionally, a third approach is developed (Scenario 3) and applied solely for the linking of groups. It is a two-stage MILP model which links dynamically the groups.

6.3.1 Sequencing the Family blocks using TSP

The TSP model requires as an input a changeover matrix. This matrix is calculated using a modified recipe list. As mentioned, the family blocks are now represented only by the first and last recipe of the block (see Section 5.2.1.1). Using the optimal sequence per block as presented from Table 17 to Table 21, the modified recipe list is finally formulated and presented in Table 26.

Table 26 Modified Recipe Input for TSP

	A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
A_K _6	0	5	0	0	0	0	4	12	11	6	0	0	27	0	14
A_Y_9	0	5	0	0	0	0	4	12	11	6	0	0	20	27	0
C_K_68	0	5	26	0	0	30	4	13	0	6	7	0	0	28	15
C_Y_5	0	5	26	0	0	30	4	13	0	6	0	0	21	0	27
M6_C_2	0	0	26	22	23	9	4	12	8	6	0	16	0	0	0
M6_M_5	0	0	26	22	23	9	4	12	8	6	0	0	0	18	0
M7_C_12	0	0	0	22	23	9	4	12	8	6	0	16	27	0	29
M7_M_19	0	0	0	22	23	9	4	12	8	6	0	27	29	18	0
P6_76	0	24	26	0	0	0	0	0	1	6	0	3	0	0	0
P4_10	0	0	25	0	0	0	4	0	0	0	0	0	0	0	0

Based on Table 26, the changeover matrix can be constructed following the methodology described in Section 4.2.1.4 but it needs to be modified further. The reason for modifying the changeover matrix is due to modeling reasons:

1) First reason is to keep the family cohesion. A family is represented as block and is seen as has only one input and one output. To avoid splitting the family block during the process, the cost from going an input recipe to an output recipe within a family block was replaced by zero cost. This ensures that the family block always stays linked together.

2) Second reason is to avoid invalid sequences. The connection between families happens when linking the output recipe of a family block to the input recipe of another family block. Hence, to avoid connections such as output to output recipe a prohibitive cost (100) was assigned to these cases.

The modified matrix for the TSP is shown in Table 27. Finally, Table 28 presents the solution that TSP model proposes.

Table 27 Changeover matrix for TSP

	A_K_6	A_Y_9	C_K_68	C_Y_5	M6_C_2	M6_M_5	M7_C_12	M7_M_19	P6_76	P4_10
A_K _6	0	0	8	6	9	9	7	9	8	7
A_Y_9	3	0	8	100	9	100	9	100	8	100
C_K_68	8	8	0	0	10	9	12	12	9	8
C_Y_5	6	100	4	0	9	100	10	100	8	100
M6_C_2	9	9	10	9	0	0	3	4	8	8
M6_M_5	9	100	9	100	2	100	5	100	9	100
M7_C_12	7	9	12	10	3	5	0	0	11	10
M7_M_19	9	100	12	100	4	100	4	100	11	100
P6_76	8	8	9	8	8	9	11	11	0	0
P4_10	7	100	8	100	8	100	10	100	6	100

Table 28 Results Overview after Sequencing within Families

TSP	Sequence	Total Actual Chgv	Waste [kg]	Cost [€]
Linking	M6→ M7→ CL→ A → P	25	4000	1613.5

6.3.2 Sequencing the Family blocks using the Group Technology Heuristic

This heuristic proposed the investigation of 3 linking scenarios (2a, 2b and 2c). The results obtained by applying this method are presented in Table 29.

Table 29 Summarized results for Group Technology scenarios

Group Technology	Sequence	Total Actual Chgv.	Waste [kg]	Waste Cost [€]
Scenario 2a	M6→ M7→A → CL → P	24	3645	1473.5
Scenario 2b	M7→M6 →A → CL → P	25	3835	1533
Scenario 2c	M7→M6 →A → P →CL	24	3795	1557.5

6.3.3 Sequencing the Groups using 2 stage MILP model

The recipe sequence for Group 1 is the same as presented in Table 23. The sequence of the family P is adjusted based on the last recipe for Group 1, so based on CL_K_ 84. Table 30 summarizes the obtained sequence and Table 31 the overall results.

Table 30 Recipe sequencing results for Group 2 under dynamic linking

Group 2	A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
P1_1	0	0	26	0	0	9	4	0	0	6	0	0	0	0	0
P4_9	0	0	25	0	0	0	4	0	0	0	0	0	0	0	0
P3_2	0	0	26	0	0	0	4	0	0	0	0	0	0	0	0
P6_44	0	0	26	0	0	0	0	0	1	6	0	0	0	3	24
P5_12	0	0	26	0	0	0	4	0	1	6	0	0	0	3	24

Table 31 Results Overview for MILP

2 stage MILP model.	Sequence	Total Actual Chgv	Waste [kg]	Cost [€]
Linking	M6→ M7→A → CL → P	21	3300	1368.5

6.4 Comparison between Scenarios

This Section and presented all possible scenarios for obtaining one integral sequence of recipes which will be used as cyclic production schedule. The computational complexity of the problem has led to the investigation of multiple scenarios and their results are summarized in Table 32.

Table 32 Summarized results for all scenarios

Scenarios	Total Actual Chgv.	Total Waste [kg]	Total Cost [€]
Scenario 1	25	4000	1613.5
Scenario 2a	24	3645	1473.5
Scenario 2b	25	3835	1533
Scenario 2c	24	3795	1557.5
Scenario 3	21	3300	1368.5

As observed from Table 32, Scenario 3 yields better outcomes that the other scenarios. The optimal recipe sequence generates 21 changeovers and 3.3 tons of waste water which is translated into 1368.5€. The analysis of the proposed scenarios revealed that the generation of waste water increases linearly with the number of changeovers but not proportionally. For instance, one changeover might cost 139.5€ (Scenario 1-Scenario 2a) or 24.5€ (Scenario 2b-Scenario 2c). This has motivated an in-depth waste water analysis to identify what drives the waste water costs in this research setting.

6.4.1 Waste Water analysis

The amount of total waste water is calculated using the information as provided from Table 33 (same as Table 7). Table 34 presents the total waste that occurs in each scenario based on the generated number of changeovers per code. The total waste is calculated by summing the OO waste and waste for the sewer together. Recall that OO waste is a type of waste that requires additional processing before disposed. Furthermore, Table 35 provides an analytic waste water overview with regard to total OO waste.

Table 33 Waste Water Matrix

	Total [kg]	OO Waste [kg]	Sewer Waste 2 [kg]
Code 1 – PF lines (from pigment to pigment)	100	45	55
Code 2 – PF lines (from any raw material to pigment)	175	120	55
Code 3 - A lines	115	40	75
Code 4 - L, S lines	190	85	105

It is important to highlight at this point that the waste water cost is assessed based on the OO waste generated per code and not on the total volume generated. For instance, Code 4 requires 190 kg of water for cleaning the dose lines but only 40kg (OO waste) impact the cost component. On the contrary, Code 2 results in 175kg waste water with 120kg to be OO waste. As a result, waste of Code 2 is more expensive but results to less waste water volume.

Table 34 Analytic Waste Overview-Total Waste

	Number of Changeovers					Total Waste = Total OO Waste + Waste for the Sewer [kg]				
Scenarios	**1**	**2a**	**2b**	**2c**	**3**	**1**	**2a**	**2b**	**2c**	**3**
Code 1	1	3	3	2	4	100	300	300	200	400
Code 2	14	13	13	14	11	2450	2275	2275	2450	1925
Code 3	6	6	6	5	4	690	690	690	575	460
Code 4	4	2	3	3	2	760	380	570	570	380

Table 35 Analytic Waste Overview-Total OO waste

	Number of Changeovers					**Total OO Waste [kg]**				
Scenarios	**1**	**2a**	**2b**	**2c**	**3**	**1**	**2a**	**2b**	**2c**	**3**
Code 1	1	3	3	2	4	45	135	135	90	180
Code 2	14	13	13	14	11	1680	1560	1560	1680	1320
Code 3	6	6	6	5	4	240	240	240	200	160
Code 4	4	2	3	3	2	340	170	255	255	170

The comparison between Scenario 1-Scenario 2b and Scenario 2b-Scenario 2c is shown in Table 36 and

Table 37 respectively.

Table 36 Comparison between Scenario 1 & Scenario2a

	Scenario 1		**Scenario 2a**	
	Number of Changeovers	Total OO Waste [kg]	Number of Changeovers	Total OO Waste [kg]
Code 1	1	45	3	135
Code 2	14	1680	13	1560
Code 3	6	240	6	240
Code 4	4	340	2	170
Total	25	1613.5€	24	1473.5€

Table 37 Comparison between Scenario 2b & Scenario2c

	Scenario 2b		**Scenario 2c**	
	Number of Changeovers	Total OO Waste [kg]	Number of Changeovers	Total OO Waste [kg]
Code 1	3	135	2	90
Code 2	13	1560	14	1680
Code 3	6	240	5	200
Code 4	3	255	3	255
Total	25	1533€	24	1557.5€

Scenario 1 and Scenario 2a changeovers are mostly concentrated on Code 2 and 4 which are the most expensive waste cost sources. On the contrary, Scenario 2b and Scenario 2c have a more uniform changeover distribution among the dose lines which yields to better results. This observation highlights the fact that the effectiveness of an optimal recipe sequence cannot only be assessed based on the resulting number of changeovers.

7 Model Implementation

7.1 Base line

In this section the performance of the best strategy (Scenario 3) is compared to the base line. The base line reflects the current production schedule in the pilot plant. Table 38 depicts the recipe sequence the corresponding allocation as applied in the pilot plant. With respect this information the performance of the pilot plant is assessed and summarized in Table 39.

Table 38 Recipe Sequence- Baseline

Base	A1	A2	A3	A4	A5	A6	A7	L1	L2	S2	S4	PF1	PF2	PF3	PF4
A_K	0	5	26	22	0	0	4	6	7	12	11	27	0	0	14
A_Y	0	5	26	22	0	0	4	6	7	12	11	27	21	0	0
A_M	0	5	26	22	0	0	4	6	7	12	11	27	0	18	0
A_C	0	5	26	22	0	0	4	6	7	0	0	16	0	0	27
NC7	0	0	26	22	23	9	4	6	0	12	8	16	0	27	29
NC4	0	0	26	22	23	9	4	6	0	12	8	16	0	0	0
NY7	0	0	26	22	23	9	4	6	0	12	8	0	21	27	29
NY4	0	0	26	22	23	9	4	6	0	12	8	0	20	0	0
NM7	0	0	26	22	23	9	4	6	0	12	8	27	28	18	0
NM4	0	0	26	22	23	9	4	6	0	12	8	0	0	18	0
NK7	0	0	26	22	23	9	4	6	0	12	8	27	29	0	14
NK4	0	0	26	22	23	9	4	6	0	12	8	0	0	0	14
C_M	0	5	26	0	30	0	4	6	7	13	27	0	0	19	0
C_K	0	5	26	0	30	0	4	6	7	13	28	0	0	0	15
C_C	0	5	26	0	30	0	4	6	7	13	27	17	0	0	0
C_Y	0	5	26	0	30	0	4	6	7	13	27	0	21	0	0
P_6	0	0	26	0	0	0	0	6	0	0	0	0	0	0	1
P_5	0	0	26	0	0	0	0	6	0	0	0	0	0	0	1
P_1	0	5	26	0	0	9	4	6	0	0	0	0	0	0	0
P_2	0	0	26	0	0	0	4	0	0	0	0	0	0	0	0
P_4	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0
P_3	0	5	26	0	0	9	4	6	0	0	0	0	0	0	0

Table 39 Base line results

	Total Actual Chgv.	**Total Waste [kg]**	**Total Cost [€]**
Baseline	21	3465	1428

cla

Table 40 Analytic waste overview of the base line

Scenario 2b	Number of Changeovers	Total OO Waste [kg]	Total Sewer Waste [kg]	Total Waste/Code [kg]
Code 1	3	135	165	300
Code 2	12	1440	660	2100
Code 3	1	40	75	690
Code 4	5	425	525	380

7.2 Model Implementation

This section presents the results after comparing the base line and the method suggested in Scenario 3. It is worth to mention that the results from Scenario 3 were modified because 5 raw materials (3, 4, 10, 24 and 25) are dosed manually whereas has been included in the proposed model. The results from the modified Scenario 3 are summarized in Table 41 and Table 42.

Table 41 Results Overview – Scenario 3 modified results and Scenario BB

Scenarios	Total Actual Chgv.	Total Waste [kg]	Total Cost [€]
Scenario 3 (mod)	17	3010	1256

Table 42 Analytic Waste Overview for modified Scenario 3

Scenario 3 (mod)	Number of Changeovers	Total OO Waste [kg]	Total Sewer Waste [kg]	Total Waste/Code [kg]
Code 1	4	180	220	400
Code 2	11	1320	605	1925
Code 3	1	40	75	115
Code 4	3	255	315	570

Table 43 Comparison between baseline and modified Scenario 3

Scenarios	Total Actual Chgv.	Total Waste [kg]	Total Cost [€]	Changeovers Savings	Water Savings	Water Cost Savings
Baseline	21	3465	1428			
Scenario 3 (mod)	19	3010	1256	4.85%	13.13%	12.04%

It is worth mentioning that Scenario 3 yields to a better solution compared to the baseline including the raw materials that require manual dosing.

8 Conclusions and Recommendations

In this section, the main findings of this research are demonstrated. Section 8.1, presents the conclusions which drew based on the formulated research questions. Section 8.2 and Section 8.3 demonstrate recommendations for the ink manufacturer and for future research respectively. Lastly, Section 8.4 mentions several limitations of the study.

8.1 Research questions

1. ***What is the current production strategy for the production in the pilot plant?***

   Pilot plant does not follow a specific model for ink manufacturing. Production is triggered by Logistics department in a weekly basis. The demand is clustered according to the family indications and production is set in multiple batches to satisfy demand. Furthermore, the allocation of the raw materials in the dose lines is made based on best guesses. The current situation results in the production of every product every 8 weeks (EWE8W).

   However, a base line was constructed of testing the model. The base lines were set defined based on a list which provides the recipe sequence of 22 recipes and the corresponding allocation as they would use for a cyclic production scheduling. Therefore, the base model used for comparisons refers to a cyclic production schedule with one batch production per recipe.

2. ***What are the resulting performance levels under this strategy and the target levels set by the company for the master plant?***

   Océ has set the performance target of every product every week (EPEW) and in the current situation this target is not reached (EWE8W).

3. ***How can the performance of production system be optimized by scheduling the recipe sequence?***

   With the decomposition of the sequencing model, several strategies were developed and analyzed under different scenarios. The optimal scenario selected was Scenario 3. In this scenario, the entire data set is portioned into groups which subsequently are linked using a dynamic linking approach.

4. ***What are the expected benefits for the company, if the proposed production schedule is applied?***

   Overall, the current production schedule results in 4.85% more changeovers that generate 13.13% more waste water kilograms which is translated into 12.04% additional cost. Scenario 3 results in 21 changeovers and 3300 kg waste water which generates 1368.5€ waste water costs. Assuming an EPEW production policy and a single batch per recipe, the annual waste water amount is 178. 2 (=52*3300) tons which generate 73899€ (=52*1368.5) costs.

The modified Scenario 3, which was used to be compared with the base line, results in 17 changeovers, 3010 kg and 1256 waste water costs. The baseline is defined by 21 changeovers and 3465kg of waste water which is 1428 waste water costs. The pilot plant produces based on EPE8W, hence an entire recipe sequence (22 recipes) will be produced roughly 6.5 (=52/8) times per year. Thus, using the modified Scenario 3 the annual amount of waste water generated is 19,56 waste water tons (baseline: 22,54 tons) and 8164 € water waste costs (baseline: 9282€). Hence, the proposed methods result in 2,95 tons less waste water and 1119€ less costs.

8.2 Recommendations

As seen, the number of changeovers depends on: 1) the sequence of the recipes (sequence dependent changeovers) and 2) the raw material allocation. As see, the flex dose lines create multiple options for raw material allocation per recipe. This flexibility has introduced computational complexity. The MILP model couldn't handle large data sets leading to the development of different strategies to obtain the final solution. In dynamic environments it is necessary to have modeling tools that provide a solution quick and fast. By reducing the number of allocation options (either by restricting the number of flex lines or investing on new dose lines), the solution search space for the model will be reduced. As a result, the model will able to provide an optimal solution once applied in a timely manner.

As mentioned, the number of allocation options can be reduced either by restricting the number of flex lines or investing on new equipment. Investing on new equipment is a scenario with limited chances since the master plant is constructed. Hence, the first option is more realistic to explore. As resulted from the analysis in Section 6.4.1, waste water costs share a linear but not proportional relationship with the number of changeovers. This observation can be used to guide the process of flex lines restriction. The focus should be placed on restricting the dose lines which generate a big amount of OO waste. So, the focus should first be placed on restricting L and S lines (Code 4), then PF lines that are associated with waste Code 2. Next, A lines should be restricted and finally, PF lines that generate waste Code 1.

Last recommendation concerns the formulation of the future recipes. The recipe congruency is a factor which stimulate the number of changeovers. When recipes differ in a great extent in terms of raw materials inevitably more changeovers are required during switching the production. Clearly, a system which operates with high incompatible product portfolio results in many changeovers. Thus, developing recipes with many raw materials in commons will result to a smoother transition between recipes in terms of the number of changeovers.

The decision-makers must take this recommendations into especially when applying the EPEW production strategy. The repetition of a fix production schedule with an overloaded number of changeovers will result in suboptimal way of working. Instead, keeping the system as simple as possible will benefit both production scheduling and planning strategies to be more agile.

8.3 Future research

Based on the conducted research study several suggestions for the future research were identified. These can be highlighted as follows:

1. As first step on the future work would be to include in the model:
    a. **Penalty costs regarding the set of dose lines.** Applying penalty costs in the set of dose lines which generate OO waste will restrict the frequent changeovers in this area resulting in less waste water generation**.**
    b. **Penalty costs regarding the cleaning. As mentioned, in this model the** minor and major set ups were treated equally. By assigning penalties in recipe sequences which result in high major set up number, thus larger freshwater consumption, the model would lead to a "leaner" solution.
    c. **Inventory and Ink perishability.** Ink is perishable product (up to 16 months). Thus, it is necessary to use SAP system to track the inventory levels per ink type and the remaining shelf life. This information can be used as an input for the model and schedule production according to the corresponding needs.

2. A further future step would be to apply the detailed scheduling of production in which the complete production line is considered. This would result to a production schedule providing the exact time of execution per recipe in the planning horizon.

8.4 Limitations

Although the research has reached its aims, there were some unavoidable limitations. Another limitation concerns the production environment that this method can be applied. The current method is most preferable to be applied in environments where the demand and processing times do not vary substantially. The total demand under EPEW policy is distributed evenly across the week. To ensure that the recipe sequence is applicable for the entire portfolio, the demand across different SKU's should not fluctuate and the processing times per product should not deviate. This will also ensure a more balance batch size per recipe and smoother production enabling the execution of the recipe sequence.

Last limitation concerns the model design, During the changeover calculations it was impossible to exclude the transition from an empty state to a raw material or the transition from a raw material to an empty state. In real world, the dose lines do not return to an empty state if the next recipe does not use the same dose line. This resulted in overestimating the number of changeovers and requiring manually work to obtain the actual number.

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