FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Production System Analysis: a Simulation Based Approach

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DISSERTATION
FINAL VERSION

MESTRADO INTEGRADO EM ENGENHARIA ELECTROTÉCNICA E COMPUTADORES

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July 2016

Abstract

With the rise of company's competiveness and a growing global market, the necessity of tools and strategies that can deliver higher product or service value are on demand [1]–[3].

In a time were there had been a converging levelling of production philosophies and tools, like *Lean*, the necessity for the next step is raising [4]–[6]. Many like Schroer et al. [7] believe that's exactly where simulation can help. Because not all tools can be applied in the same standard way or neither can they all be of simple comprehension regarding the pursue of improvements, because of the need for decision and strategies support in opposition to conjectures or guesses, it is why manufacturing systems simulation and modelling could and should be the next evolutionary step.

In that matter it must be acknowledge that some companies already use these tools with great sophistication and knowledge like General Electric, Intel, AirBus Group [8], Price Water Coopers (PWC), Infineon [9], Port of Hamburg [10], Telefonica and Alcatel Lucent [11] but that is still short. Because of the low cost and de great advantages, improvements and cost reduction [12], in short term the majority of companies should converge to this reality.

Some of the reasons for this delay have been pointed out by McLean et al. [13], Fowler et al. [14] e Abdulmalek et al. [15], being the major one the lack of commitment and confidence of managers with these tools, usually replaced with more complex and less effective ones.

The main goal of this dissertation was to analyse and evaluate simulation software through implementation of production system tools aiming to improve the facility layout design. Followed by the creation of a tool that could determine optimal facility layout results for complex routings, specific input and output points, fixed and heterogeneous shapes with different department proportions.

The objectives are the investigation of the benefits and difficulties of using these simulation tools as well as the improvements that could be implemented in a scenario like this. For this purpose, it will be used a case study of a production system modeled with discrete events through AnyLogic simulation software.

Acknowledgments

I would like to thank my supervisors, Professor Jorge Pinho de Sousa and Samuel Moniz for the support and guidance during this dissertation.

Secondly, to my girlfriend Filipa Ferreira for the unconditional help and love specially on the difficult times.

To my father, for the continuous support all these years even when it was hard, my mother for the positive attitude and belief in me and to my sister for the friendship, this achievement is also yours.

To the Real República dos LYS.O.S., my second home and to all the brothers I have made in the last years of the course.

I'm grateful for the all the professors and colleagues that shared knowledge and friendship aiding to the development of what I'm today.

And finally to Sociedade de Debates da Universidade do Porto for helping me develop my communication skills.

Edgar Bento

“One of the greatest discoveries a person makes, one of their great surprises, is to find they can do what they were afraid they couldn't do.”

- Henry Ford

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Abbreviations

BOM	Bill of Materials
CONWIP	Constant Work-in-Progress
CRAFT	Computerized Relative Allocation of Facilities Technique
FEUP	Faculdade de Engenharia da Universidade do Porto / Faculty of Engineering of University of Porto
FLP	Facility Layout Problem
GA	Genetic Algorithm
GPSS	General Purpose Simulation System
GT	Group Technology
IMVP	International Motor Vehicle Program
INESC TEC	Institute for Systems and Computer Engineering, Technology and Science
JIT	Just-in-time
KPI	Key Performance Indicator
MPS	Master Production Schedule
MRP	Material Requirement Plan
MTO	Make-to-Order
MTS	Make-to-Stock
OEE	Overall Equipment Effectiveness
QAP	Quadratic Assignment Problem
SA	Simulated Annealing
SMED	Single Minute Exchange of Die
SS	Safety Stock
TPM	Total Productive Maintenance
TPS	Toyota Production System
UML	Unified Modeling Language
UP	University of Porto
VS	Value Stream
VSM	Value Stream Mapping
WIP	Work-in-Progress

Chapter 1

Introduction

This dissertation was developed under the Integrated Master in Electrical and Computer Engineering, Faculty of Engineering of Porto (FEUP).

The present chapter introduces the project, its contextualization regarding the subject, problem and research question, the objectives, the adopted methodology and planning and finally the document structure.

1.1 Keywords

Manufacturing Systems Design, Facility Layout Problem, CRAFT, Buffer Sizing, Manufacturing System Simulation, Discrete Event Simulation.

1.2 Contextualization and Problem

At the present time and due to a competition growth associated with a global market it is important to guarantee an efficient, effective and fast production system management given the rapid changes in the world's context and scenarios.

Earlier, the evolution jump was attached to the implementation of a new management philosophy. "Lean Manufacturing" started in Japan with the Toyota Production System, looking to reduce waste and therefore increase productivity and gains.

Nowadays, with the methodology convergence the margin for error has decreased. Thus, it can be observed a growth in the need to test new hypothesis, diminish errors, anticipate scenarios, and to have the data and conclusions which support and justify the decision making and strategies [4]–[6].

In response to these felt needs, solutions have appeared, each time more sophisticated and complete than before [16]–[18]. In this context the simulation starts to win even more a bigger relevance. Today hold like one of the most powerful tools to be used in production system analysis. It can assess the impact on systems parameters variations and increase the chance for success of informed decisions based on multi-scenarios [19].

Even though manufacturing simulation is believed to have great advantages its utilization is not growing accordingly. Some of the reasons for this delay have been pointed out by McLen et al. [13], Fowler et al. [14] e Abdulmalek et al. [15], being the major one the lack of commitment and confidence of managers with these tools, usually replaced with more complex and less effective ones.

Regarding the facility layout problem, the optimal design of the physical layout is one of the most important issues to be considered in the early stages of the design of a manufacturing system. Tompkins et al. [20] estimated that 15± 70% of the total operating expenses within manufacturing systems are attributed to material handling, and that these costs can be reduced by at least 10± 30% through a good layout planning. Furthermore, the system efficiency and work-in process inventory are also significantly affected by layout design.

Therefor this dissertation tries to evaluate one of these tools regarding the implementation of several production system methodologies and addresses the development of a tool for layout optimization given the specific case study.

Research questions:

1. What is the potential of simulation software in the manufacturing systems?
2. What kind of constrains and difficulties can be found to the implementations of these models?
3. How can simulation aid the improvement of the facility layout design?

1.3 Motivation and Goals

The drive of this project lies in the possibility to develop a simulation of discrete events model that can help in a company's production system analysis. Thus, this practical case study, through distinct scenarios creation can allow real improvements which could be an interesting feature for the verification of theoretical concepts interaction with the actual practical application.

Making, this way, possible to evaluate and analyze changes of several production variables, look for improvements, understand certain events, predict future situations and ultimately help the decision making so that is sustained, informed and riskless.

Furthermore, regarding the facility layout, Drira et al. [21] estimated that 20–50% of the manufacturing costs are due to the handling of parts and then a good arrangement of handling devices might reduce them for 10–30%. Thus developing a tool that can aid the optimization process and incorporate the simulation results can deliver great outcomes that could point the right path to an increase in productivity and profit.

1.4 Methodology

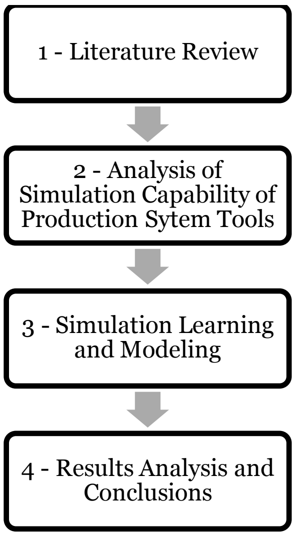


Figure 1 - Project Methodology

The methodology for this project can be divided in four main parts.

Firstly, the process started with the search, reading and gathering of literature that relates to this project and its goals. The major topics addressed were: Lean Manufacturing Systems, Discrete Event Simulation, Manufacturing System Simulation, and Facility Layout Design. This initial step is one of the more importance given it gives un understanding of all concepts, a background in history and evolution of them and defines a clear path of choices that can be taken.

The second was the analysis production system tools and their capacity to be simulated with the project constrains. Given that some could be easily calculated with non-simulated methods, and for the purposes of the global improving it was concluded that the study of the facility layout design could be a great value added in this step.

Thirdly, the simulation part, it was conduced a deep study and learning of AnyLogic software and JAVA language, the later was needed given that AnyLogic software uses JAVA as the lower level language to be embedded in the properties and functionalities, resulting in a better and closer to reality model. Following by the model implementation, test and record of results, being this process developed with PDCA methodology because of the continuous need for change and adaptation.

Lastly the fourth part groups the results analysis and the conclusions of the project. Given that the part 2 and 3 were related, it was needed a new part regarding the analysis of the results as one to evaluate their relations and in that matter what changes could be triggered by the findings in the previous results. This process terminates with the conclusions of the all project.

1.5 Planning

Next follows the description of the activities and provided planning Figure 2, given the expected duration of the dissertation.

- Research and gathering of state of art towards discrete events simulation in production systems concepts and methodologies.
- JAVA and AnyLogic software learning followed by the modelation of the production system
- Results study and analysis.
- Writing the Dissertation.
- Preparation of the final presentation
- Final Review of the Dissertation

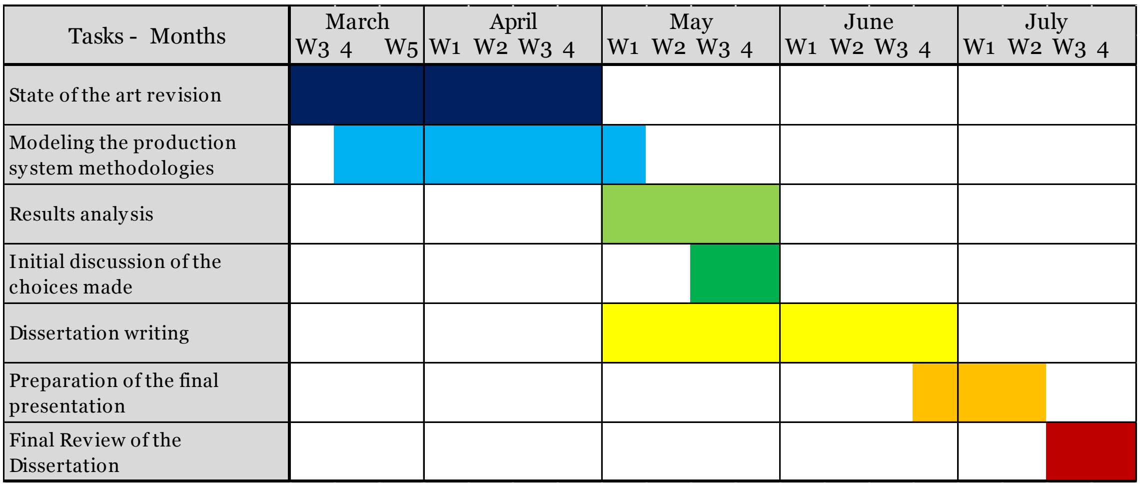


Figure 2 - Gantt Chart

1.6 Document Structure

Besides this introduction, this dissertation is presented with 5 more chapters.

The second chapter describes the state of art of the subjects being study and gives some historical view over the evolution of the lean methodologies in the manufacturing systems. Chapter 3, methodology, presents and discusses the methods undertaken to answer the research questions.

The fourth chapter analyses the results given by the previous chapter and explains how can the practical approach and the simulation one can relate and complement each other to a greater solution in the end.

The last chapter presents the overall conclusions of the work followed by the appendixes, with auxiliary information regarding code, the model, the excel evaluation tool and the case study, and with the references and the additional bibliography.

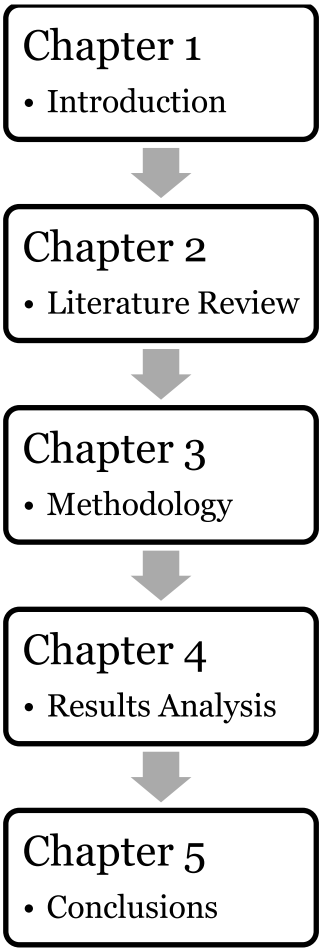


Figure 3 - Document Structure

Chapter 2

Literature review

This chapter presents the major theoretical concepts that support the following work.

Firstly, a description of inventory and buffers is given, demonstrating the importance and necessity of each subject in production systems.

Secondly it is shown different production strategies and the respective characteristics, when should be applied, benefits and disadvantages.

Thirdly the facility layout literature review gives a deeper insight to the topic and resolution methods.

Fourthly the Simulation literature is addressed presenting the major advantages and drawbacks of its use.

Lastly it is presented the benefits of discrete event simulation regarding its use to model production system tools and methods.

2.1 Inventory

Nicholas Chase et al. [22] presents the definitions, “Inventory is the stock of any item or resource used in an organization”, and “An inventory system is the set of policies and controls that monitor levels of inventory and determine what levels should be maintained, when stock should be replenished, and how large orders should be.”

An inventory can be helpful to a company in various ways [22]:

- To maintain independence of operations – where a line of production of a part doesn’t depend directly of the line of production of other parts and keep its own production flow.
- To meet variation in product demand
- To allow flexibility in production scheduling
- To provide a safeguard for variation in raw material delivery time
- To take advantage of economic purchase order size

Any alterations made to the inventory size should at all times consider some costs [22]:

- Holding costs
- Setup costs
- Ordering costs
- Shortage costs

2.2 Buffer

The buffer storage emerged through the necessity to reduce machine unpredictability, variability of break downs, unbalance processing times and fluctuated production requirements. Therefor it serves to decouple machines and mitigate these variables.

On the other side, the implementation of buffer storage has an impact on the performance characteristics such as productivity, flexibility, and space utilization so the buffer size calculation is an important aspect of a manufacturing system [23].

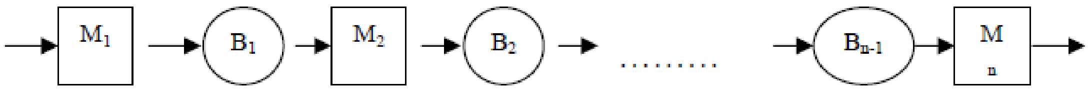


Figure 4 - Machine flow line with buffers [24]

Figure 4 represents production line with buffer storage, where the squares, letters M, represent the machines and the circles, letters B, represent the buffers.

2.3 Push and Pull Production Systems

At this point it will be presented, discussed and compared two production strategies, Push and Pull.

2.3.1 Push

Push production had its origin with mass production era. Zheng and Xiaochum [25] agree that this kind of production starts with the forethought, followed by fabrication process development and lastly the management system implementation and production control.

Push production or make-to-stock (MTS), search for a given master production schedule (MPS) based on demand study and forecast, to push the merchandize to the market making it available for consumers. For that to happen, the same push process is made to push the supplies since the start, through several processes till the system end, then being storage in the warehouse and available to distributors.

Zheng et al., Krishnamurthy et al. and Zhou et al. [25]–[27] acknowledge also that one of the major advantages of this system is the ability to increase output and equipment usage. The main disadvantage lies in the considerable increase of product inventory and risk of mistaken forecasts says Zheng.

Figure 5 illustrates the push production where you can easily see that for a certain demand forecast the production is started, ending usually in the merchandize storage in warehouse which then go to distribution.

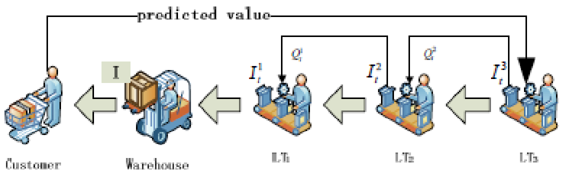


Figure 5 - Push Type Production [25]

2.3.2 Pull

In order to eliminate one of the wastes, Toyota created a system called Just-In-Time, JIT, allowing inventory reduction considered a form of waste by his own definition, the *muda*. As Zhen and Xiaochun [25] explain, this waste reduction, caused by excessive production for instance, is made through JIT, using Kanban's which together demand a pull production.

A pull production or make-to-order (MTO) is based on consumer's current demand. For this reason the production process begins with the income of consumer orders which make a pull, of the supply necessary to the processes within the production system.

Hopp et al., Savsar et al., Spearman et al. e Deleersmyden et al. and Zheng et Xiaochun [25], [28]–[31] highlight several advantages, being the inventory reduction the major one, but on the other hand there is a possibility to increase the delivery's delay.

Figure 6 represents the functioning of pull production system.

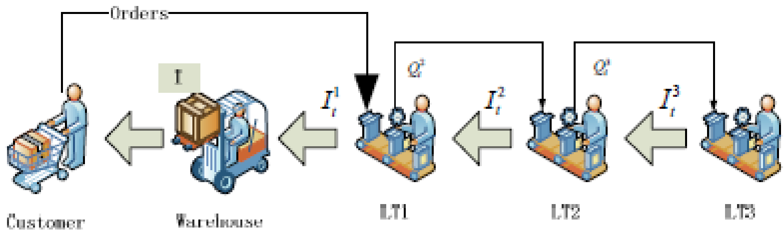


Figure 6 - Pull Production System [25]

2.3.3 Comparison between Pull and Push Production Systems

In the following table it is represented the main issues concerning with each production method usage.

Table 1 - Comparação dos sistemas de Produção Pull e Push[25]

	Push System	**Pull System**
Driving Mode	Production Plan	Customer Orders
Scale & Flexibility	Mass production, Low cost	Customization production
Inventory	Higher inventory level	Low inventory levels
Order completion time	Lower response time	A certain delay
Equipment utilization	Higher capacity utilization	Customer order-related

2.3.4 Conclusions

Through these two systems comparison as Zheng et al., Spearman et al., Timsit et al. and Toni et al. [25], [30], [32], [33] suggest we can conclude that each has its advantages and disadvantages, but aren't necessarily better than the other. The adequate production system depends on the business model or productive strategy.

Analyzing more complex strategies [34], CONWIP-Pull, Hybrid Push/Pull we can in a certain way use the advantages of each type and comparatively reduce the disadvantages, but the application must be done with a broad knowledge of the production system in question.

2.4 Facility Layout

Facility layout is a part of facilities design, which embraces other issues such as plant location, building design, material handling, etc.

It generally includes a study of the production line process flow charts, product routings, processing times, material flow diagrams, development of from-to charts, relationship diagrams between different departments in the facility and the cost of material movement [35].

2.4.1 Basic Production Layout Formats

According to [22] there are three basic types (process layout, product layout, and fixed-position layout) and one hybrid type (group technology or cellular layout).

Many manufacturing facilities present a combination of two layout types. For example, a given production area may be laid out by process, while another area may be laid out by product. It is also common to find an entire plant arranged according to product layout – for example, a parts fabrication area followed by a subassembly area, with a final assembly area at the end of the process. Different types of layouts may be used in each area, with a process layout used in fabrication, group technology in subassembly, and a product layout used in final assembly.

2.4.1.1 Process Layout

“A process layout, also known as job-shop or functional layout, is a format in which similar equipment or functions are grouped together, such as all lathes in one area and all stamping machines in another”[22]. A part being worked on then travels, according to the established sequence of operations, from area to area, where the proper machines are located for each operation. This type of layout is typical of hospitals, for example, where areas are dedicated to particular types of medical care, such as maternity wards and intensive care units [22].

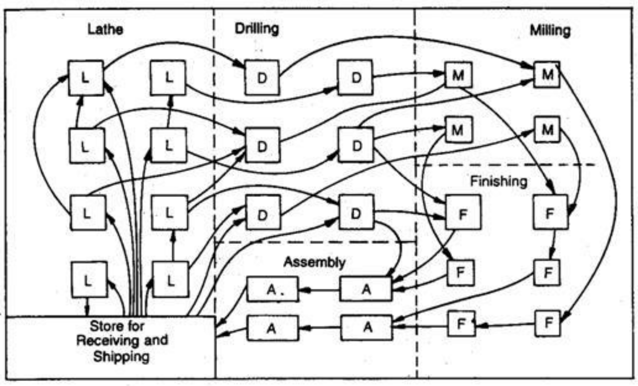


Figure 7 - Process Layout [67] [1]

[1] http://www.transtutors.com/homework-help/industrial-management/plant-layout/process-layout.aspx

2.4.1.2 Product Layout

“A product layout, also known as flow-shop layout, is one in which equipment or work processes are arranged according to the progressive steps by which the product is made”[22]. The path for each part is, in effect, a straight line. Production lines for shoes, chemical plants, and car washes are all product layouts [22].

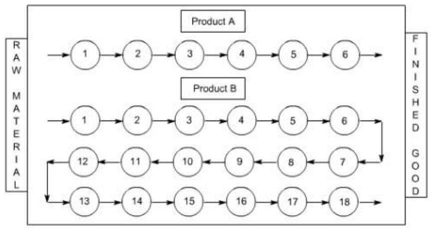


Figure 8 - Product Layout [67]

2.4.1.3 Group Technology

“A group technology layout, also known as cellular layout, groups dissimilar machines into work centers (or cells) to work on products that have similar shapes and processing requirements”[22]. A group technology (GT) layout is similar to a process layout in that cells are designed to perform a specific set of processes, and it is similar to a product layout in that the cells are dedicated to a limited range of products. Group technology also refers to the parts classification and coding system used to specify machine types that go into a cell [22].

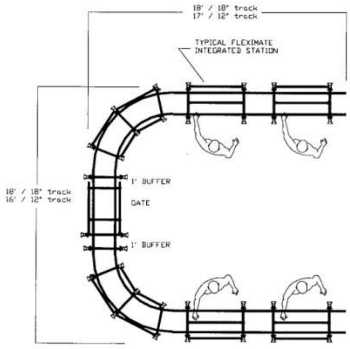


Figure 9 - Cellular layout [68]

2.4.1.4 Fixed-Position Layout

In a fixed-position layout, the product (by virtue of its bulk or weight) remains at one location. Manufacturing equipment is moved to the product rather than vice versa. Construction sites and movie lots are examples of this format [22].

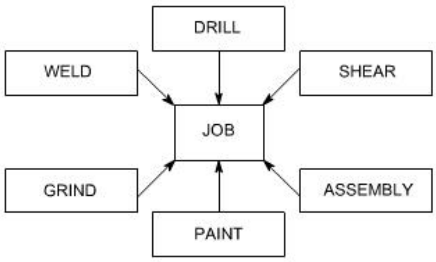


Figure 10 - Fixed-Position layout [67]

2.4.2 Facility Layout Problem

Determining the physical organization of a production system is defined to be the facility layout problem (FLP). Where to locate facilities and the efficient design of those facilities are important and fundamental strategic issues facing any manufacturing industry. [36]

The placement of the facilities in the plant area, often referred to as “facility layout problem”, is known to have a significant impact upon manufacturing costs, work in process, lead times and productivity [6]. A good placement of facilities contributes to the overall efficiency of operations and can reduce until 50% the total operating expenses [20].

Reduced material movement lowers work-in-process levels and throughput times, less product damage, simplified material control and scheduling, and less overall congestion. Hence, when minimizing material handling cost, other objectives are achieved simultaneously.

The output of the FLP is a layout that specifies the relative location of each department. Detailed layout of a department can also be obtained later by specifying aisle structure and input/output point locations which may include flow line and machine layout problems. [36]

Unfortunately, layout problems are known to be complex and are generally NP-Hard [37].

2.4.2.1 Inputs/Constraints

In general, the inputs to layout decisions are as follows [22]:

1. Specifications of the objectives and the corresponding criteria to be used to evaluate the design. The amount of space required, and the distance that must be travelled between elements in the layout.
2. Estimates of product or service demand on the system.

3. Processing requirements in terms of number of operations and amount of flow between the elements in the layout
4. Space requirements for the elements in the layout
5. Space availability within the facility layout, or if this is a new facility, possible building configurations

2.4.2.2 SLP – Systematic Layout Planning

SLP is a way of approaching the conception or reorganization of a workplace, for example a factory layout meant for manufacturing various products. The main goal in this context is to create an even more efficient layout[38]–[40]. SLP methodology uses five basic elements for a layout planning:

- Product (P) – products to be made, raw materials, acquired parts, semi-finished and finished products;
- Quantity (Q) – the amount of products to be made or of materials to use. The quantities can be valued by number of parts, weight, dimension, produced value or selling value;
- Technology (R) – scheme of operations, points out which equipment and tools to use as well as the workers that will complete the tasks;
- Support (S) – jobs and functions that are necessary beyond the transforming operations itself, namely, maintenance, inspection, storage, provision, etc.;
- Production Timing (T) – amount of time which allows defining precisely when the products should be made, the timings of the several tasks, etc.

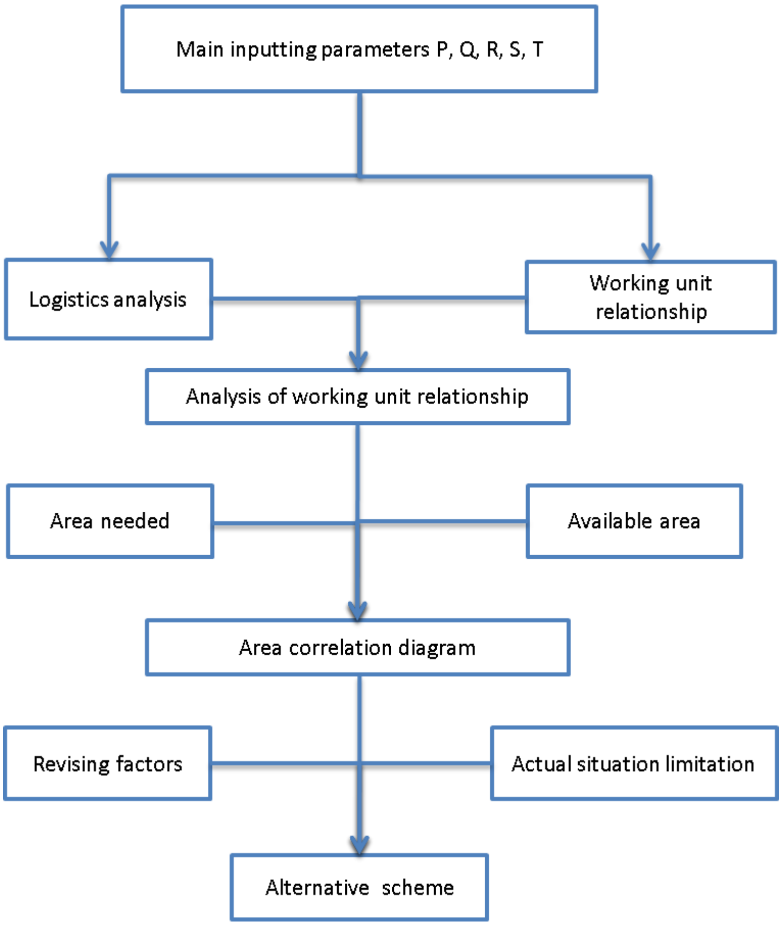


Table 2 - Systematic Layout Planning [38]

2.4.3 Solution methodology

In this section various solution methodologies, e.g. exact procedures, heuristics and meta-heuristics available to solve facility layout problems optimally or near to optimal, are discussed in detail. [36]

2.4.3.1 Exact procedure

Among articles that dealt with exact methods, the branch and bound algorithm for the unidirectional loop layout problem developed by Kouvelis and Kim [41] is one of the most important. Branch and bound methods are used to find an optimum solution of quadratic assignment formulated FLP because QAP (Quadratic Assignment Problem) involves only binary variables. The Quadratic Assignment Problem (QAP) of order n, as explained by Maniezzo et al., consists of looking for the best allocation of n activities facilities to n locations, where the terms activity and location should be considered in their most general sense [42].

With a large scale problem it becomes intractable for a computer to solve and, consequently, even a powerful computer cannot handle a large instance of the problem [36].

Accordingly to our bibliographic review, we can say that despite all the continuous evolution in computers and computing ability, in which Moore's Law [43] stipulates the doubling in circuit complexity every 18 months, the issue still lies.

Since exact approaches are often found not to be suited for large size problems, numerous researchers have developed heuristics and meta-heuristics [21].

2.4.3.2 Heuristics

Heuristic algorithms can be classified as construction type algorithms [36].

Construction approaches build progressively the sequence of the facilities until the complete layout is obtained whereas improvement methods start from one initial solution and they try to improve the solution with producing new solution [21].

Construction based methods are considered to be the simplest and oldest heuristic approaches to solve the QAP from a conceptual and implementation point of view, but the quality of solutions produced by the construction method is generally not satisfactory. Improvements based methods start with a feasible solution and try to improve it by interchanges of single assignments. Improvement methods can easily be combined with construction methods.[36]

CRAFT is a popular improvement algorithm that uses pair- wise interchange [44] later on, this specific method will be addressed further.

These heuristics are classified as adjacency and distance based algorithms.[36]

The difference between these two algorithms lies in the objective function. The objective function for adjacency based algorithms is given as equation (1):

$$\text{Max} \sum_{i} \sum_{j} (r_{ij}) x_{ij} \tag{1}$$

Where x_{ij} is 1 if department 'i' is adjacent to department 'j' and else 0. The basic principle behind this objective function is that the material handling cost is significantly reduced if the two departments have adjacent boundaries. The objective function of distance based algorithms is given as equation(2):

$$\text{Min(TC)} = \frac{1}{2} \sum_{\substack{i=1 \\ i \neq k}}^{n} \sum_{\substack{j=1 \\ j \neq l}}^{n} \sum_{k=1}^{n} \sum_{l=1}^{n} C_{ik} * D_{jl} * X_{ij} * X_{kl} \tag{2}$$

The underlying philosophy behind this objective function is that the distance increases the total cost of traveling. C_{ik} can be replaced by F_{ik} depending on the objective. Equation (3) is used as an objective function when the facility layout is designed for multi-floor.

$$\min \sum_{\substack{i=1 \\ i \neq k}}^{n} \sum_{\substack{j=1 \\ j \neq l}}^{n} \sum_{k=1}^{n} \sum_{l=1}^{n} \left(C_{ikH} * D_{jlH} * C_{ikV} * D_{jlV} \right) * X_{ij} * X_{kl} \tag{3}$$

Where, C_{ikH} and D_{jlH} stand for horizontal material handling cost and horizontal distance, respectively. The same meanings are applicable for C_{ikV} and D_{jlV} but in vertical directions.

2.4.3.3 Meta-heuristics

Various meta-heuristics such as simulated annealing (SA), genetic algorithm (GA), and ant colony are currently used to approximate the solution of very large FLP. The SA technique originates from the theory of statistical mechanics and is based upon the analogy between the annealing of solids and solving optimization problems [36].

GA gained more attention during the last decade than any other evolutionary computation algorithms; it utilizes a binary coding of individuals as fixed-length strings over the alphabet {0,1}. GA iteratively search the global optimum, without exhausting the solution space, in a parallel process starting from a small set of feasible solutions (population) and generating the new solutions in some random fashion. Performance of GA is problem dependent because the parameter setting and representation scheme depends on the nature of the problem.

Tabu search (TS) is an iterative procedure designed to solve optimization problems. The method is still actively researched, and is continuing to evolve and improve. Recently, a few papers have appeared where an ant colony algorithm has been attempted to solve large FLP [36].

Other approaches which are also currently applied to FLP are neural network, fuzzy logic and expert system.

2.4.4 Computerized Relative Allocation of Facilities Technique - CRAFT

Computerized Relative Allocation of Facilities Technique CRAFT is the archetypal improvement-type approach and was developed by Armour and Buffa [44] in 1963. CRAFT begins by determining the centroid of each department in the initial layout. It then performs two-way or three-way exchanges of the centroids of non-fixed departments that are also equal in area or adjacent in the current layout. For each exchange, CRAFT will calculate an estimated reduction in cost and it chooses the exchange with the largest estimated reduction (steepest descent). It then exchanges the departments exactly and continues until there is not any estimated reduction due to two-way or three-way exchanges. Constraining the feasible department exchanges to those departments that are adjacent or equal in area is likely to affect the quality of the solution, but it is necessary due to its exchange procedure. [45]

The objective of the algorithm is to minimize total cost (TC). The function is represented by the following equation (4)

$$\mathrm{TC} = \sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij} \times W_{ij} \times C_{ij} \tag{4}$$

D_{ij} is the distance from departments i to department j.
W_{ij} is the interdepartmental traffic from departments i to department j
C_{ij} is the handling cost between departments i and department j [46]

2.5 Simulation

At this point is made a presentation of the main simulation aspects applied to production systems.

Negahban et al. and Smith [18], [47] identify in their studies about design simulation literature and production systems operation that simulation has been having a fundamental part in analysis and optimization of industrial management area, such in design as in operation of production systems.

They conclude as well that this is a growing reality due to the need to evaluate lean philosophy's implementations and to preview future alterations, changes or new strategies, diminishing the risk, increasing scenario development and strengthening decisions.

2.5.1 Introduction

The word simulation can be defined in several ways:

- Ingals [48] introduces simulation as "a powerful tool if understood and used properly".
- Banks [49] says that " simulation is the imitation of the operation of a real-world process or system over time. Simulation involves the generation of an artificial history of the system, and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system that is represented."
- Shannon [50] defines simulation as "the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and /or evaluating various strategies for the operation of the system".

As simulation is according to these authors the imitation or the system drawing process or industrial processes, in this case, using close to reality models, it matters also to define model and system.

- Maria [51] defines model as "a representation of the construction and working of some system of interest. A model is similar to but simpler than the system it represents.
- Shannon [50] claims that "by a model we mean a representation of a group of objects or ideas in some form other than that of the entity itself."

Regarding a system, the same author declares:

- Shannon [50] that "by a system we mean a group or collection of interrelated elements that cooperate to accomplish some stated objective.

2.5.2 Methodology for a Simulation Process

The creative process of a simulation model varies with the need or application, but generally there are several similar steps.

Fowler [14] suggests that a production system analysis using simulation involves the following process:

- Model Design
  - Identify the issues to be addressed
  - Plan the project
  - Develop the conceptual model
- Model Development
  - Choose a modeling approach
  - Build and test the model
  - Verify and validate the model
- Model Deployment
  - Experiment with the model
  - Analyze the results
  - Implement the results for decision making

Maria [52] identically identifies the phases of this kind of project and explains in what way the simulation can be used continuously promoting an also continuous improvement as shown in Figure 11.

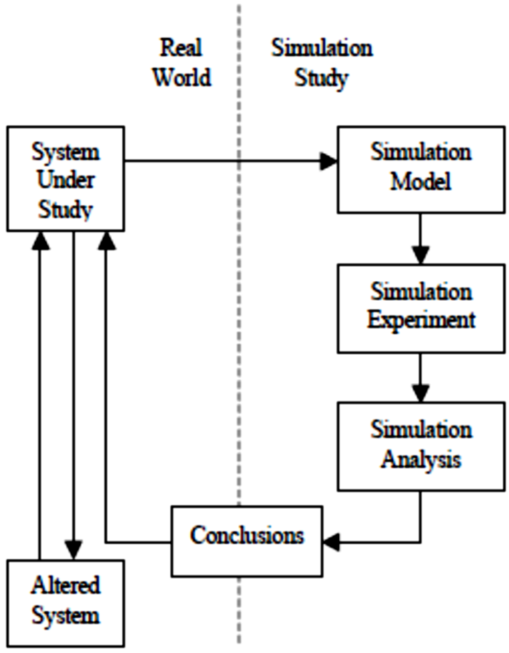


Figure 11 - Simulation Study Design [52]

2.5.3 Steps in a Simulation Study

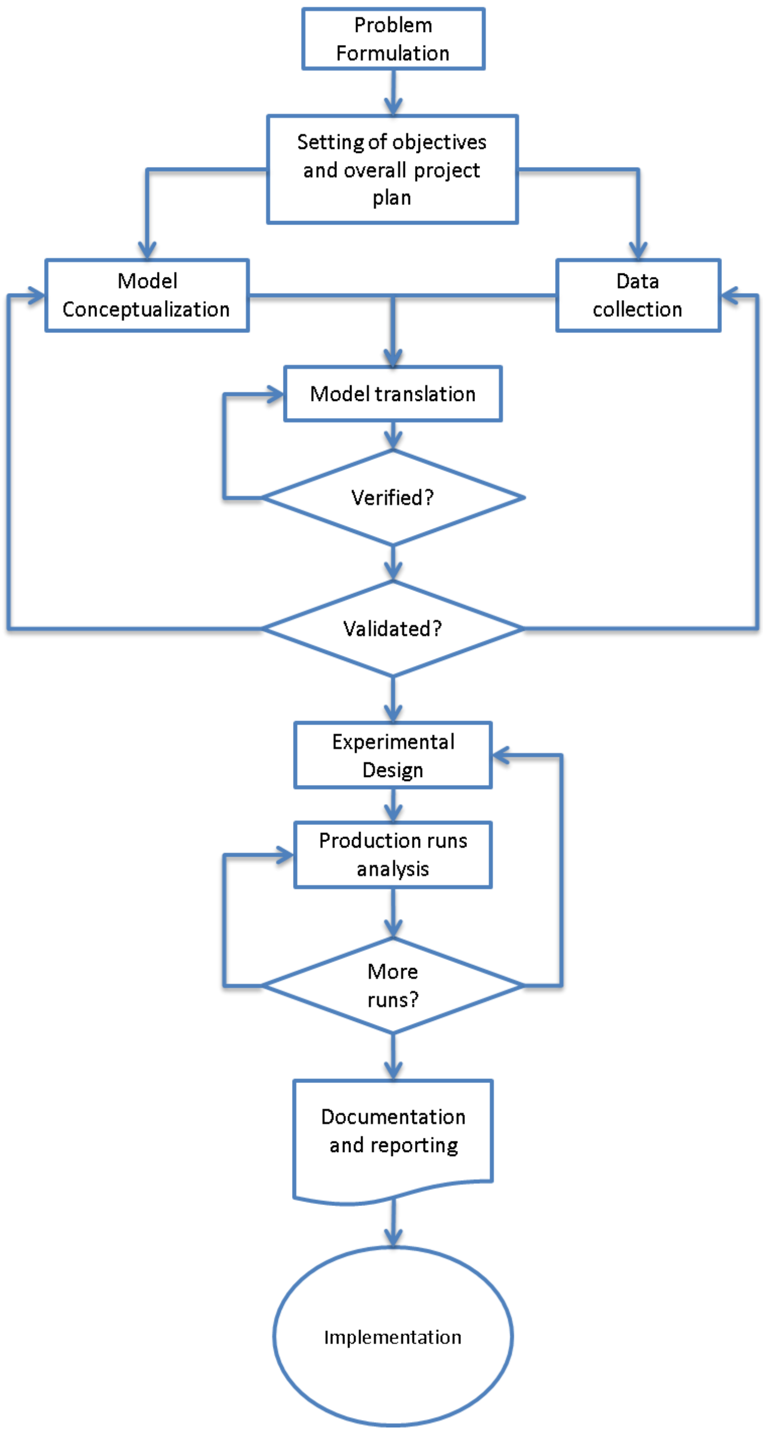


Figure 12 - Steps in a Discrete Simulation Study [53]

Table 3 - Steps in a Discrete Simulation – Definitions [53]

Steps	Definition
Problem formulation	• Requires the definition of the problem ensuring its clear understanding. • Sometimes the problem needs to be reformulated due to the course of the study.
Objectives and Overall Project Plan	• Indicates questions to be answered by simulation. • Revision of the methodology to apply. • Includes: different stages of the study, time required for each stage, cost of study, number of people needed, and expected results.
Model Conceptualization	• Starting point with a basic model and built upon it • Get the essence of the real system
Data Collection	• Important to collect from the beginning because it is time consuming • "constant interplay between construction of the model and data collection
Model Translation	• Transforming the real problem into computational form • Choice of language to program the model
Verified?	• Achieved naturally through common sense • Verify if everything is running properly
Validated?	• Accepted certainty level in which the model represents the real system • Same expected outcome than in real system • Minimizing the discrepancies between the model and the real system
Experimental Design	• Try and fail/succeed to consider all the alternatives • Reach the final model with the best choices
Production Runs and Analysis	• Estimate measures of performance for the simulated scenarios.
More Runs?	• Deciding if it is necessary to run more simulations
Documentation and reporting	• Program documentation – if a program has multiple users; easier to understand how it works; keeping track of modifications • Progress documentation – Chronology of the project; checking if whether the work is up to date or not • Reports – Insight of others on the progress; early catch of any issues or doubts and easy solutions
Implementation	• Depends on the quality of the previous steps; • If a previous step was neglected , some issues will surface during this step

2.5.4 Simulation Models Characteristics

The simulation models can be characterized as statics or dynamic, deterministic or stochastic and continuous or discrete, according to several authors as explain Reeb e Leavengood [54].

A static model represents the system in a given moment whereas a dynamic one represents how the system evolves through time. The static model examples are, for instance casino games simulation such as roulette, cards, dice, etc. Here, the time factor is irrelevant cause doesn't conditions in any way the simulation. Regarding to dynamic models, typically are all those who represent a process behavior through time, a boiler warm-up, the making of a given part, etc. are dynamic.

In a deterministic model, doesn't exist variation in the model parameters or in its variables, if it is fed the same values on its way in, it will always calculate the same exit. This way it can simulate the trajectory of a baseball ball including the laws of physics involved in the model.

On the other hand, a stochastic model contains at least one random variable to describe the process within the system of study. This difference results that the exit results are mere estimates of the true model characteristic. These situations happen, for instance, in the randomness in which a customer arrives to a bank balcony among other similar.

Regarding a continuous system its main characteristic is the status variables to vary continuously. The examples are simulation of vehicle movement, liquid flows, chemical reactions, electronic circuits and econometric models, etc.

Lastly Reeb et al [54] explains that in a discrete system the variables change only in a given number of points in time. Examples include traffic control, distribution system and stock control, production lines simulation, production systems as a whole, etc.

Analyzing the problem involved it can be envisaged that it will be a dynamic simulation model by discrete events, eventually stochastic due to error randomness, damages and other simulating factors.

2.5.5 Simulation Benefits and Disadvantages

According to Shannon [50] these are the major simulation advantages:

- We can test new designs, layouts, etc. without committing resources to their implementation.
- It can be used to explore new staffing policies, operating procedures, decision rules, organizational structures, information flows, etc. without disrupting the ongoing operations.
- Simulation allows us to identify bottlenecks in information, material and product flows and test options for increasing the flow rates.
- It allows us to test hypothesis about how or why certain phenomena occur in the system
- Simulation allows us to control time. Thus we can operate the system for several months or years of experience in a matter of seconds allowing us to quickly look at long time horizons or we can slow down phenomena for study.

- It allows us to gain insights into how a modeled system actually works and understanding of which variables are most important to performance.
- Simulation's great strength is its ability to let us experiment with new and unfamiliar situations and to answer "what if" questions.

The same author refers that, though the simulation has many advantages it also has some disadvantages. Mainly being:

- Simulation modeling is an art that requires specialized training and therefore skill levels of practitioners vary widely.
- The utility of the study depends upon the quality of the model and the skill of the modeler.
- Gathering highly reliable input data can be time consuming and the resulting data is sometimes highly questionable. Simulation cannot compensate for inadequate data or poor management decisions.
- Simulation models are input-output models, i.e. they yield the probable output of a system for a given input. They are therefore "run" rather than solved. They do not yield an optimal solution, rather they serve as a tool for analysis of the behavior of a system under conditions specified by the experimenter.

In this point Maria [52] also presents the benefits and traps of these model simulations. Of note, the following traps especially:

- Unclear objective
- Using simulation when an analytic solution is appropriate
- Invalid model
- Simulation model too complex or too simple
- Erroneous assumptions
- Undocumented assumptions. This is extremely important and it is strongly suggested that assumptions made at each stage of the simulation modeling and analysis exercise be documented thoroughly.
- Using the wrong input probability distribution
- Replacing a distribution (stochastic) by its mean (deterministic).
- Using the wrong performance measure
- Bugs in the simulation program
- Using standard statistical formulas that assume independence in simulation output analysis.
- Initial bias in output data
- Making one simulation run for a configuration
- Poor schedule and budget planning
- Poor communication among the personnel involved in the simulation study.

2.5.6 When Simulation is not appropriate

Table 8 summarizes what Banks et al. [53] and Banks and Gibson [55] thought about when simulation would be a problem. For that they created a 10 rule approach to help the simulation model developers determine whether to use or not simulation in a specific problem.

Table 4 - 10 Rules When Simulation is not Appropriate

# Rules	Description
1	When the problem can be solved using common sense
2	When the problem can be solved analytically
3	When it is easier to perform direct experiments
4	When the costs exceed the savings
5	When the resources are not available
6	When the time is not available
7	When there is not any data available
8	When it is not possible to verify or validate the simulation model
9	When the power of simulation is overestimated
10	When the system behavior is too complex or cannot be defined

Adapted from [53], [55].

2.5.7 Areas of Application

On Table 5 is presented the typical areas of application and some examples to enhance understanding.

Table 5 - Areas of Application. Adapted from [53]

Areas of Application	Examples
Manufacturing Applications	• Analysis of electronics assembly operations • Design and evaluation of a selective assembly station for high-precision scroll compressor shells • Comparison of dispatching rules for semiconductor manufacturing using large-facility models • Evaluation of cluster tool throughput for thin-film head production • Determining optimal lot size for a semiconductor back-end factory • Optimization of cycle time and utilization in semiconductor test manufacturing • Analysis of storage and retrieval strategies in a warehouse • Investigation of dynamics in a service-oriented supply chain • Model for an Army chemical munitions disposal facility
Semiconductor Manufacturing	• Comparison of dispatching rules using large-facility models • The corrupting influence of variability • A new lot-release rule for wafer fabs • Assessment of potential gains in productivity due to proactive reticle management • Comparison of a 200-mm and 300-mm X-ray lithography cell • Capacity planning with time constraints between operations • 300-mm logistic system risk reduction
Construction Engineering	• Construction of a dam embankment • Trenchless renewal of underground urban infrastructures • Activity scheduling in a dynamic, multiproject setting • Investigation of the structural steel erection process • Special-purpose template for utility tunnel construction

Areas of Application	Examples
Military Applications	• Modeling leadership effects and recruit type in an Army recruiting station • Design and test of an intelligent controller for autonomous underwater vehicles • Modeling military requirements for non-warfighting operations • Multi-trajectory performance for varying scenario sizes • Using adaptive agents in US Air Force pilot retention
Logistics, Transportation, and Distributions Applications	• Evaluating the potential benefits of a rail-traffic planning algorithm • Evaluating strategies to improve railroad performance • Parametric modeling in rail-capacity planning • Analysis of passenger flows in an airport terminal • Proactive flight-schedule evaluation • Logistics issues in autonomous food production systems for extended-duration space exploration • Sizing industrial rail-car fleets • Product distribution in the newspaper industry • Design of a toll plaza • Choosing between rental-car locations • Quick-response replenishment
Business Process Simulation	• Impact of connection bank redesign on airport gate assignment • Product development program planning • Reconciliation of business and systems modeling • Personnel forecasting and strategic workforce planning
Human Systems	• Modeling human performance in complex systems • Studying the human element in air traffic control

2.5.8 Systems and System Environment Definition

- System – "group of objects that are joined together in some regular interaction or interdependence toward the accomplishment of some purpose".[53]
- System Environment – a system can be influenced by external factors mainly in its surroundings. "In modeling systems, it is necessary to decide on the boundary between the system and its environment." This decision reflects on the purpose of the study.[53]

2.5.9 Examples of Components of a System

Table 6 presents examples of the typical components of a simulation System.

Table 6 - Components of a Simulation System – Adapted from [53]

System	Entities	Attributes	Activities	Events	State Variables
Banking	Customers	Checking account balance	Making deposits	Arrival; departure	Number of busy tellers; number of customers waiting
Rapid rail	Riders	Origination; destination	Traveling	Arrival at station; arrival at destination	Number of riders waiting at each station; number of riders in transit
Production	Machines	Speed; Capacity; Breakdown rate	Welding; stamping	Breakdown	Status of machines (busy, idle, or down)
Communications	Messages	Length; destination	Transmitting	Arrival at destination	Number waiting to be transmitted
Inventory	Warehouse	Capacity	Withdrawing	Demand	Levels of inventory; backlogged demands

2.5.10 Simulation Modeling Approaches

Simulation follows three different types of modelling approaches, System Dynamics, Discrete Event and Agent Based. The following topics present the main characteristics of each one.

2.5.10.1 System Dynamics modelling

System Dynamics was created by Jay Forrester in the 1950s, his idea was to describe the dynamics of economic and social systems through the laws of electrical circuits.

System dynamics is a method of studying dynamic systems. It suggests that you should [56]:

- Take an endogenous point of view. Model the system as a causally closed structure that itself defines its behaviour.
- Discover the feedback loops (circular causality) in the system. Feedback loops are heart of system dynamics.
- Identify stocks (accumulations) and the flows that affect them. Stocks are the memory of the system, and sources of disequilibrium.
- See things from a certain perspective. Consider individual events and decisions as "surface phenomena that ride on an underlying tide of system structure and behaviour." Take a continuous view where events and decisions are blurred.

System dynamics is positioned as a strategic modelling methodology with high abstraction level.

Models of social dynamics, epidemics, or consumer choice, individual people are aggregated into stocks (compartments) and sometimes segmented into gender, education, income level, etc.[56]

2.5.10.2 Discrete Event modelling

Discrete event modelling was introduced by Geoffrey Gordon in the 1960s with General Purpose Simulation System. Nowadays (GPSS), this type of modelling is supported by many software tools, including modern versions of GPSS itself.

"The idea of discrete event modelling method is this: the modeller considers the system being modelled as a process, i.e. a sequence of operations being performed across entities."

Typical operations include delays, service by various resources, choosing the process branch, splitting, combining, and some others. As long as entities compete for resources and can be delayed, queues are present in virtually any discrete event model.

The model is specified graphically as a process flowchart, where blocks represent operations aided by textual languages as well, but they are in the minority.

Flowcharts usually start with "source" blocks that generate entities and inject them into the process, and ends with "sink" blocks that remove entities from the model.

This type of diagram is familiar to the business world as a process diagram and is ubiquitous in describing their process steps being one of the reasons why discrete event modelling has been the most successful method in penetrating the business community.

Patients, phone calls, documents (physical and electronic), parts, products, pallets, computer transactions, vehicles, tasks, projects and ideas are represented as agents and for example staff, doctors, operators, workers, servers, CPUs, computer memory, equipment and transport as resources.

Entity arrival times and service times are usually stochastic, drawn from a probability distribution. Therefore, discrete event models are stochastic themselves which implies that a model must be run for a certain time, and/or needs a certain number of replications, before it produces a meaningful output.

The typical output expected from a discrete event model is:

- Utilization of resources
- Time spent in the system or its part by an entity
- Waiting times
- Queue lengths
- System throughput
- Bottlenecks
- Cost of the entity processing and its structure

Discrete event modelling is significantly lower than that of system dynamics; the diagram mirrors sequential steps that happen in the physical system and each object in the system is represented by an agent or a resource unit, and keeps its individuality.[56]

2.5.10.3 Agent Based modelling

Agent based modelling is one of the most recent modelling methods that turned up in the 2000s. [56]

It was triggered by:

- Desire to get a deeper insight into systems that are not well-captured by traditional modelling approaches
- Advances in modelling technology coming from computer science, namely object oriented modelling, UML, and state charts
- Rapid growth of the availability of CPU power and memory (agent based models are more demanding of both, compared to system dynamics and discrete event models).

Agent based modelling suggests to the modeller yet another way of looking at the system.

- You may not know how the system as a whole behaves, what are the key variables and dependencies between them, or simply don't see that there is a process flow, but you may have some insight into how the objects in the system behave individually. Therefore, you can start building the model from the bottom up by identifying those objects (agents) and defining their behaviours.
- Sometimes, you can connect the agents to each other and let them interact; other times, you can put them in an environment, which may have its own dynamics. The global behaviour of the system then emerges out of many (tens, hundreds, thousands, even millions) concurrent individual behaviours.

Adapted from [56]–[60].

"Agent based modelling does not assume any particular abstraction level. If agents are individuals, then the agent based model is certainly more detailed than a segmented system dynamics model where individuals are aggregated based on characteristics. Agent, however, can be developed with high level of abstraction. For example, the agents may be competing projects, companies, or even ideas or philosophies".[56]

2.6 Production System Tools and Methods Review using Discrete Event Simulation

This topic presents a review of several production system tools and presents the advantages and difficulties of using discrete event simulation to model them.

It was considered several methods and tools but regarding the project approach to the production system, the following were believed to be more relevant.

Bottleneck Analysis

Bottleneck analysis allows identifying where in the production process is happening throughput limitation.

As an advantage, enables throughput improvement through the system weakest link strengthening.

This analysis can be made through simulation, both for the current factory situation as for the previous analysis of future alterations or line expansion or production processes. [61]

Continuous Flow

Is a production style where the WIP naturally flows through various processes with minimum or none buffer between all several steps.

It cuts out some of waste forms as waiting time, inventory and transportation, for example. It can be simulated and verified through simulation.[61]

Heijunka (Level Scheduling)

It is a way of production scheduling that deliberately produces in small batches, sequencing different products in the same process.

It allows reducing lead time and inventorying. It can be simulated and it's a good way to identify several kinds of waste cause typically reveals many inefficiencies that are hiding due to big inventories.[61]

Just-In-Time (JIT)

It is a strategy that pulls the product through the various stations based on consumer's demand instead of push that produces based on what was initially projected.

Highly effective in inventory levels reduction, lowers as well the need for space and increases financial flows.

Its efficiency can be verified through simulation using different demand scenarios or even through simulation of a random demand.[61]

Kanban (Pull System)

Method used to regulate the product flow within a company. Based on the automatic supply of products in a station through a card like sign, that indicates when more products are needed.

It can be simulated through the creation/programming of rules that create electronic Kanban's of similar functioning to physical ones. Therefore, a pull system application can be simulated using Kanban's. [61], [62]

KPI (Key Performance Indicator)

Metric designed to register and encourage the progress of critical goals to the organization. Strongly promoted KPI's can be behavior motors and so it is extremely important to choose the desired KPI's.

The effects can't be simulated but results and information can be extracted to help this metric's construction, whether in the identification of the best and most suitable indicators or in the study of those indicators.

Muda

It refers to all within the production process that doesn't add value from the customer's perspective. The main focus in a lean production system is cutting out the waste. Relatively to the Toyota Production System (TPS) there are 7 muda's.

- Transportation – Each time a product is moved it stands the risk of being damaged, lost, delayed, etc. as well as being a cost for no added value. Transportation does not make any transformation to the product that the consumer is willing to pay for.
- Inventory – Inventory be it in the form of raw materials, work-in-progress (WIP), or finished goods, represents a capital outlay that has not yet produced an income either by the producer or for the consumer. Any of these three items not being actively processed to add value is waste.
- Motion – Refers to the damage that the production process inflicts on the entity that creates the product either overtime (wear and tear for equipment and repetitive strain injuries for workers) or during discrete events (accidents that damage equipment and/or injure workers).
- Waiting – Whenever goods are not in transport or being processed they are waiting. In traditional processes, a large part of an individual product's life is spent waiting to be worked on.
- Over-processing – Occurs any time more work is done on a piece other than what is required by the customer. This also includes using components that are more precise, complex, higher quality or expensive than absolutely required. (Traditional notion of waste, as exemplified by scrap that often results from poor product or process design).
- Over-production – Occurs when more products are produced than is required at that time by your customers. One common practice that leads to this *muda* is the production of large batches, as often consumer needs change over the long times large batches require. Overproduction leads to excess inventory, which then requires the expenditure of resources on storage space and preservation, activities that do not benefit the customer.
- Defects – Whenever defects occur, extra-costa are incurred reworking the part, rescheduling production, etc. This results in labor costs, more time in the WIP. Defects in practice can sometimes double the cost of one single product. This should not be passed on to the consumer and should be taken as a loss.

Through simulation all the waste described can be verified and simulated. Even though it is important to consider that for the simulation and identification of all of these to happen, it would take a rather complex and realistic system, which held information about a great number of variables.

Overall Equipment Effectiveness (OEE)

It is a type of metric used to measure the productivity loss to a certain productive process. Three kinds of losses are evaluated, availability (down time), performance (slow cycles) and quality (rejected).

Offers a base line/reference and the means to register the waste elimination progress, 100% means a perfect production; producing good parts, as fast as possible without any down time due to damages.

It can be simulated through model. It can be a good evaluation measure for the various productive scenarios as shown by Gibbons [63].

Root Cause Analysis

It is a problem resolution methodology that focuses on the problem source instead the quick fixing of symptoms.

Helps insure that the problem is truly eliminated through corrections on the problem source.

The simulation due to its ability to control time and isolate certain processes can be a help in the identification of the problems and its sources.

Six Big Losses

This refers to six categories of productivity loss which are felt almost universal in production systems:

- Malfunction
- Setup time
- Small stops
- Speed reduction
- Rejection of the first pieces
- Rejects due to production

This permits identifying and attacking the most common causes of waste in production systems.

These issues can be simulated in order to identify the consequences of these kinds of productivity losses looking for solutions and avoid their existence.

Takt Time

Guides the way in which the feedstock goes through processes. Takt means compass, rhythm. This tool application gives a simple, consistent and intuitive way of giving rhythm to the production.

This technique can be simulated in order to get the application consequences or takt time changes [7].

Value Stream Mapping

A tool used to visually map the production flow and also the future procedure status in order to reach improvement opportunities.

Exposes the waste present in current procedures and presents a guiding way to its improvement [64].

It can be reached through simulation as explained by Jarkko et al. and Abdulmalek et al. [5], [15].

Buffer Sizing

Several studies have explored the buffer problem [23], [24], [65]–[67] regarding different methods and approaches including the analytic method, gradient search, experimental design, and heuristics.

Furthermore the apparent computational difficulty has led to the majority of buffer sizing approaches to be heuristic-oriented [23], but more recent articles point the benefits of computational studies which allows the study of any production line configuration, which is hard (or sometimes even impossible) to analyse using theoretical approaches and allows the study of cases in which the random variables that govern the behaviour of the system are characterized by any general distribution. [24].

Lee et al. also concludes that the one computational approach can is efficient and flexible for determining buffer storage in both serial production lines and more complex manufacturing systems. [23].

Simulation of Facility Layout Problems

Aleisa and Lin [68] raise the important question in their study "For effectiveness facilities planning: Layout optimization then simulation or vice-versa?" The resume can be found in the table Table 7 - Layout than Simulate or vice versa

Table 7 - Layout than Simulate or vice versa [68]

Paradigm	Layout then simulate	Simulate then layout
Belief	Simulation analysis is local, where layout optimization analysis is global	Simulation prior layout study produces layouts that are efficient and realistic
Benefits	Time efficient	Provides accurate estimate of flow for layout optimization simulation
Application (Best for)	• Improving existing layout • Resolving congestion and bottlenecks in layout • Only minor system's process' parameters need to be adjusted • Technology embraced requires special layout type and simulation for verification • Insignificant stochastic behaviour • Focus is on minimizing travelled distance	• Creating a new layout for a system that exhibit significant: – stochastic behaviour/demand • and/or – complex interactions • Major operational policies/technologies are not predetermined or need to be justified prior layout optimization • Simulation is used to generate random flow to be fed for a layout routine • Solving flow congestions and bottlenecks have higher priority than reducing distances

To conclude they believe that the choice of the approach depends on the objectives and the characteristics of the system.

Chapter 3

Methodology

Previously it was defined the research questions for this project:

1. What is the potential of simulation software in the manufacturing systems?
2. What kind of constrains and difficulties can be found to the implementations of these models?
3. How can simulation aid the improvement of the facility layout design?

Regarding these questions, the methodology chapter discusses the how, the why and the what.

How was the research made to answer these questions?
Why was it made with these approaches and not others?
What was specifically developed to achieve those goals?

Firstly, a brief description of the case study used in this project is presented.

Secondly, and according to the previous analysis, given the constrains encountered and the rules that will be described it is developed a tool for facility layout design that can further be improved using additional information from simulation modelling focusing on question 4.

Lastly an overview of the software is made followed by the simulation model construction that trough them deliver a pathway with results to answer the first and second research questions.

3.1 Case Study

This case study has the purpose of serving as data input to the facility layout improving tool developed further and also to the simulation and modelling of the buffers and test of the limitations of a manufacturing system simulation, with a large array of products, materials with a high annual demand.

This data was presented in a need to know bases because of the necessity to respect the confidential information of the original case study. In that matter some information regarding the type of industry, what type of products produced, initial layout and other information that could present a comparison bases and confirm some of the guesses and premises where not available.

3.1.1 Characterization of the system

The object of this case study was a company of a given sector in which:

- The annual search of the manufactured products was of 357.010 units;
- Range of available products was of 68 types

The products are composed by:

- An array of material, sometimes more than one kind of material
- The products composition is available through the Table 29

Materials:

- Each type of material follows a defined route within the workstations
- The annual demand of materials was of 38.462.971
- There are 256 types of materials in this company

The simulation model needed to be able to handle more than 250 different types of materials and about 70 different types of products. Each one consists of a set of materials sometimes more than one amount of the same type of material.

Product Demand

Table 8 - Input Orders by ReleaseDate

idDemand	idComponent	releaseDate	Total Production
1	274	05-01-2015 00:00	1789
2	279	05-01-2015 00:00	1777
3	284	05-01-2015 00:00	1334
4	257	05-01-2015 00:00	1314
5	286	05-01-2015 00:00	1073
6	273	05-01-2015 00:00	992
7	259	06-01-2015 00:00	835
8	282	06-01-2015 00:00	820
9	298	06-01-2015 00:00	722
10	281	06-01-2015 00:00	658
---	---	---	---
358	295	20-02-2015 00:00	94

- "idDemand" – unique order identifying number
- "idComponent" – refers to product type, this allows to build a population of products, then used to create materials (in push production)
- "releaseDate" – day of the arrival of the order used as a trigger for each new arrival
- "Total Production" – is the amount of products needed to fulfil the order

Table 9 - Total Products Ordered and Variety in a Year

Total Product Variety	Total Products Ordered in a Year
68	357.010

There are 68 types of product with an annual demand of 357.010.

Table 10 - Materials Annual Demand

idComponent	length	Rework	Pcs/pal	Scrap		Yearly demand
1	1,8	0,01	476	0,028		132.893
2	1,8	0,01	476	0,028		132.893
3	2,1	0,01	1666	0,028		265.786
4	2,1	0,01	451	0,028		132.893
5	2,1	0,01	3608	0,028		199.339
6	1,8	0,01	276	0,028		132.893
7	1,5	0,01	238	0,028		43.174
8	1,5	0,01	238	0,028		23.650
9	1,8	0,01	238	0,028		52.622
10	2,1	0,01	102	0,028		66.446
---	---	---	---	---	---	---
256	1,8	0,01	68	0,028		1.087

Table 11 - Total Materials Yearly Demand

Total Material Variety	Total Material Yearly Demand
256	38.462.971

- “idComponent” – material type
- Total Material variety of 256 different material types
- Total material annual demand of 38.462.971

Bill of Materials

Bill of materials(BOM) is a list of raw materials or unassembled parts and quantities that constitute each product.

Table 12 - Bill of Materials

idProduct	idMaterial	materialDescription	BOM multiplier
232	69	Material_69	2
232	70	Material_70	2
233	13	Material_13	2
233	14	Material_14	2
---	---	---	---
298	65	Material_65	2
298	236	Material_236	2
298	78	Material_78	1
298	43	Material_43	1
298	16	Material_16	1
298	75	Material_75	1
298	74	Material_74	1
298	54	Material_54	1
298	52	Material_52	1
299	77	Material_77	2
299	67	Material_67	2
299	50	Material_50	1
299	17	Material_17	1

- "idProduct" – Product type
- "idMaterial" – Material type
- "BOM multiplier" – quantity of each material to compose a product

Routings

Table 13 - Routings

idMaterial	Alt	idInputMachine	idMachineString	idMachineStringAlt	ProcessingTime	ProcessingTimeAlt
1	0	M03R1			0,0023	
1	0	M11R1			0,0176	
1	0	M12R1			0	
1	1	M14R2	M14R2	M13R1	0,0526	0,1754
1	0	M19R2			0	
1		M21R1			0	

idMaterial	Alt	idInputMachine	idMachineString	idMachineStringAlt	ProcessingTime	ProcessingTimeAlt
1		Sink1			0	
---	---	---	---	---	---	---
255	1	M17R2	M17R2	M18R2	0,3922	0,3509
255	0	M21R1			0,0283	
255	0	Sink1			0	
256	1	M17R2	M17R2	M18R2	0,3922	0,3509
256	0	M21R1			0,0283	
256	0	Sink1			0	

- "idMaterial" – represents the material type
- "Alt" – Is a variable that states that there is a workstation alternative
- "idInputMachine" – represents a string sequence of workstations
- "idMachineStringAlt" – represents the workstation alternative sequence
- "ProcessingTime" – The time that each workstation takes to process a specific material
- "ProcessingTimeAlt" - The time that the alternative workstation takes to process a specific material

Setup Time

Table 14 - Setup Time

idMachine Number	MachineId	Resource	Workstation Name	Machine setup times	WorkCentre capacity
1	A	M01R1	Cutting	0,00	0,00
2	B	M02R1	Coating	0,00	0,00
3	C	M03R1	Sawing	1,00	1,00
4	D	M04R1	Wrapping	15,00	1,00
5	E	M05R1	Cross cutting	10,00	1,00
6	F	M06R1	4 side	10,00	2,00
7	G	M07R2	Drilling line	15,00	2,00
8	H	M08R1	2 sides	30,00	1,00
9	I	M09R1	Corner cutting	5,00	1,00
10	J	M10R1	Profile wrapping	35,00	1,00
11	K	M11R1	Wrapping line	30,00	1,00
12	L	M12R1	Cutting machine	5,00	1,00
13	M	M13R1	Edge banding	10,00	1,00
14	N	M14R2	Edge banding	10,00	2,00
15	O	M15R2	Hot dowling	15,00	2,00
16	P	M16R2	Friulmac	15,00	2,00
17	Q	M17R2	Frame assembly	10,00	2,00

idMachine Number	MachineId	Resource	Workstation Name	Machine setup times	WorkCentre capacity
18	R	M18R2	Auto frame assembly	10,00	2,00
19	S	M19R2	Drilling	20,00	2,00
20	T	M20R1	CNC	10,00	1,00
21	U	M21R1	Buffer	0,00	0,00
22	V	M22R3	Packing	15,00	3,00
23	W	M23R1	Rework	0,00	0,00
24	X	M24R2	Product stacking	0,00	0,00
25	Y	Sink		0,00	0,00

- "MachineId" – represents the letter identifier as mentioned above
- "Machine Setup Time" – Represents the time taken for setup of the workstation whenever a different material arrives to it
- "WorkCentre Capacity" – Represents how many materials at once can the machine deal with

Layout

The following figure represents the workstations the respective shapes and relative dimensions.

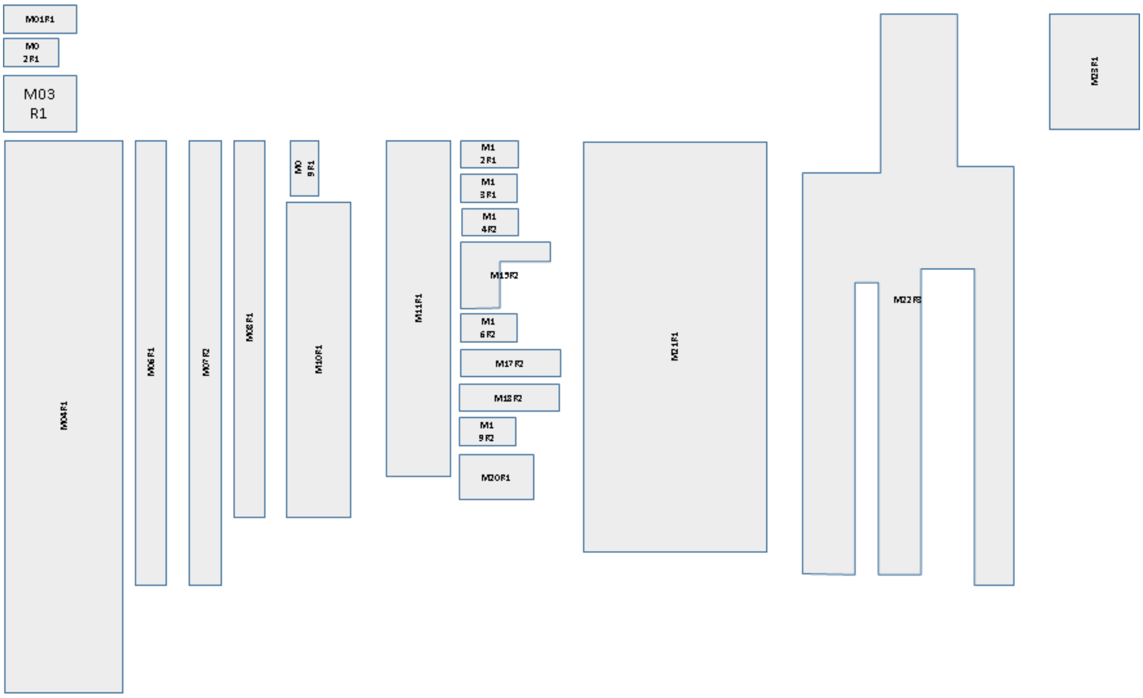


Table 15 - Work Station Relative Dimensions and Shapes

3.2 Facility Layout Design

As previous mentioned in Table 8 - 10 Rules When Simulation is not Appropriate on the topic 3.1.2 When Simulation is not appropriate, regarding the lean manufacturing design and especially the facility layout problem it were taken in consideration the following rules:

- When the problem can be solved analytically;
- When it is easier to perform direct experiments;
- When the time is not available;
- When the system behaviour is too complex or cannot be defined.

Thus, it was concluded that the facility layout problem relative to the given case study would be solved through an analytical approach rather than simulated. That approach is explained in the following topics.

3.2.1 Facility Layout Approach

The approach for this project regarding the facility layout problem was to decompose it in three main issues:

1. Layout Construction;
2. Layout Evaluation;
3. Layout Improvement.

The first topic addresses the steps taken to construct the first layout, what information was needed and what kind of analysis and filtering were made.

Second, the layout evaluation, will explain what tools and key measures were created or taken to evaluate each layout created, thus effectively supporting the improvement part.

Lastly, layout improvement, defines the iterative process taken to make incremental and improving changes through the information gathered from the layout evaluation based on intuition, judgment and experience learning.

3.2.2 Layout Construction

To construct the first layout and further ones, it was necessary to gather, filter and analyse data from the annual product demand, or selected period, and from the manufacturing process.

Necessary steps for the layout construction:

1. Collect and analyse annual/periodic product demand;
2. Calculate the respective material quantities trough bill of materials;
3. Create an interdepartmental flow table/chart;
4. Create a virtual image representation of workstations with proportionality to each other in excel;

3.2.2.1 Collected annual product demand analysis

It all started with the product demand analysis, like shown in Table 9 - Product Demand, where in this case the idComponent stands for the product identification with the respective amount, lot size and total production.

Table 16 - Product Demand

idDemand	idComponent	amount	lotsize	-	Total Production
1	274	1	1789	-	1789
2	279	1	1777	-	1777
-	-	-	-	-	-
358	295	1	94		94

Next, given the bill of materials shown in Table 10 - Bill of Materials, it was constructed the material demand table trough the relations between the product, the materials that make it (idMaterial), the bill of materials multiplier for each one, and the total production.

Table 17 - Bill of Materials

idProduct	idMaterial	materialDescription	BOM multiplier
232	69	Material_69	2
232	70	Material_70	2
233	13	Material_13	2
233	14	Material_14	2
-	-	-	-

3.2.2.2 Annual material demand trough bill of materials

With these relations between the product demand and the materials, it was build Table 11, where in this case IdComponent represents the material type.

Table 18 - Annual Material Demand

idComponent	length	Rework	Pcs/pal	Scrap	Yearly demand
1	1,8	0,01	476	0,028	132.893
2	1,8	0,01	476	0,028	132.893
3	2,1	0,01	1666	0,028	265.786

3.2.2.3 Interdepartmental flow table/chart creation

Identified the annual material demand, for the purposes of layout construction, it was necessary the manufacturing process part, regarding the flow of materials trough the respective workstations and analysis of the unique routes. Finalizing in the sorting of the data by the greatest flow of materials from one work station to another. By doing this procedure it was easily identified the greatest unique flows between workstations represented in Table 12

Table 19 – Filtered interdepartmental flow

Routing	Materials
CJ	15817669
JL	15817669
SU	13435437
CK	9736345
KL	9736345
CD	8641488
DE	8488416
FU	7924458
LN	7007820
NS	7007820
EF	6553643
LO	6467013
OU	6467013
LS	5204078
PU	3228380
HU	3042882
LP	2902798
QU	2427429
EH	1934773
LF	1662777
LH	1473529
LM	1142143
MS	1142143
RU	1126918
IU	810454
FI	445034
HI	365420
CP	325582
CL	306144
DF	153072
CS	81396

Many steps and advanced excel formulas were used to manage the information, this happened because of the huge amount of data and relations, leading to the need of automatic processes.

One of those was the simplification/substitution of the workstations names for alphabet letters, so in this table, the first letter represents the workstation of origin, the second the destination. On the next cell it is represented the volume of materials that goes from one to another.

For better interpretation of the material flow were created vitalization graphs. These kinds of tools are a great aid in the identification of some material flow characteristics.

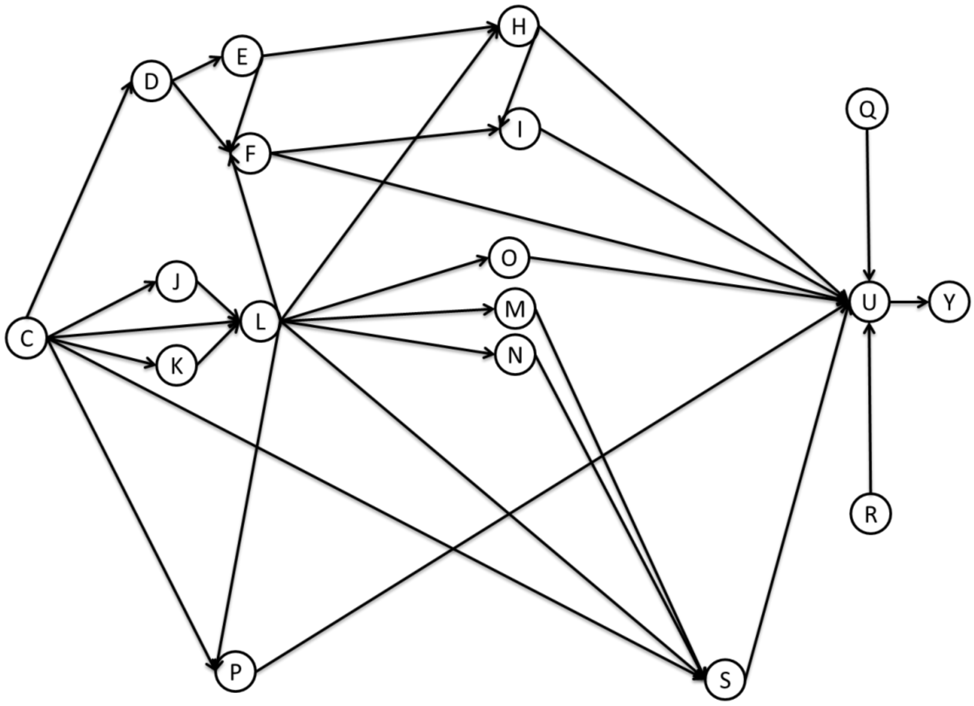


Figure 13 - Interdepartmental Flow Graph

Figure 13 shows the interdepartmental Flow Graph, one of the graphic tools build. This kind of representations normally displays the annual/periodic objects flow, but in this case, given the high volume of materials and the number of stations that would harm the visualization benefits. To solve this problem and enhance the analysis, another two graphs were created, a circular flow chart and the Sankey flow chart. Even so, in this representation it were identified several questions.

- It could be hard to eliminate the crisscrosses of the different pair connections. Examples of the routings from work station “L” to “S” and pair “L” to H”;
- The work station L is the one with more connections;
- The flow starts in work stations C, Q and R and all end in work station U;
- Some material flow starts in work stations Q and R but they travel directly to the last work station U.

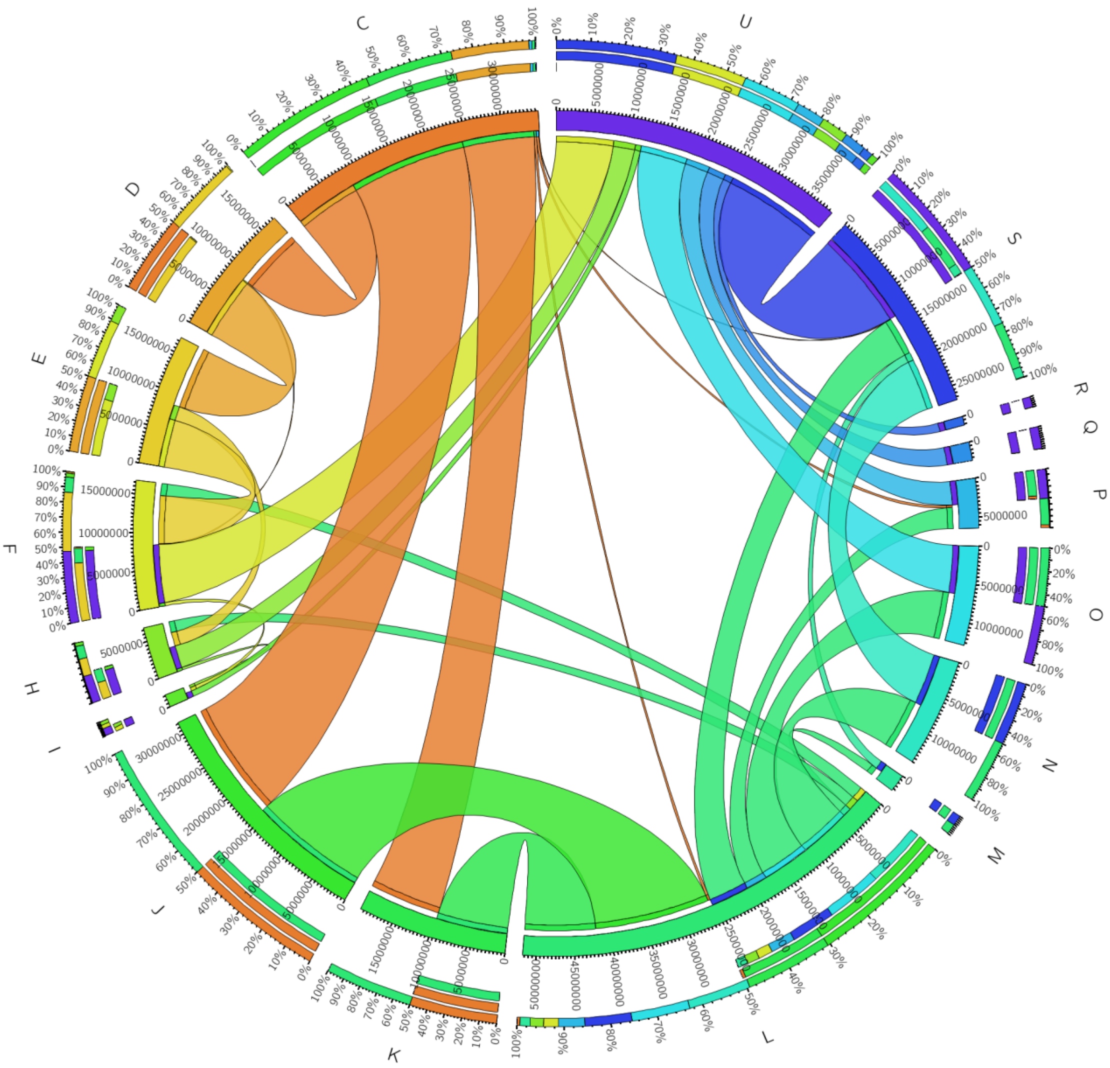


Figure 14 - CIRCOS - Circular Flow Chart [2]

In this figure, each letter represents a workstation as pointed above, and then the flow is represented from pair connections between them, being the width representative of the flow by qualitative and quantitative means.

Data input used in this flow chart creator can be viewed on Appendixes Table 41

Some characteristics can be easily identified:

- The greatest flow happens between work stations “CJ”, “CK”, “JL”, “SU”;
- Almost 70% of the initial flow, from work station “C”, goes to “J” and “K”, respectively 40% and 30%;
- All the flow that goes to “J” and “K” goes to “L” and represents almost 100% of the input materials of “L”;
- Again work station “L” has the greatest amount of connections;

[2] www.circos.ca

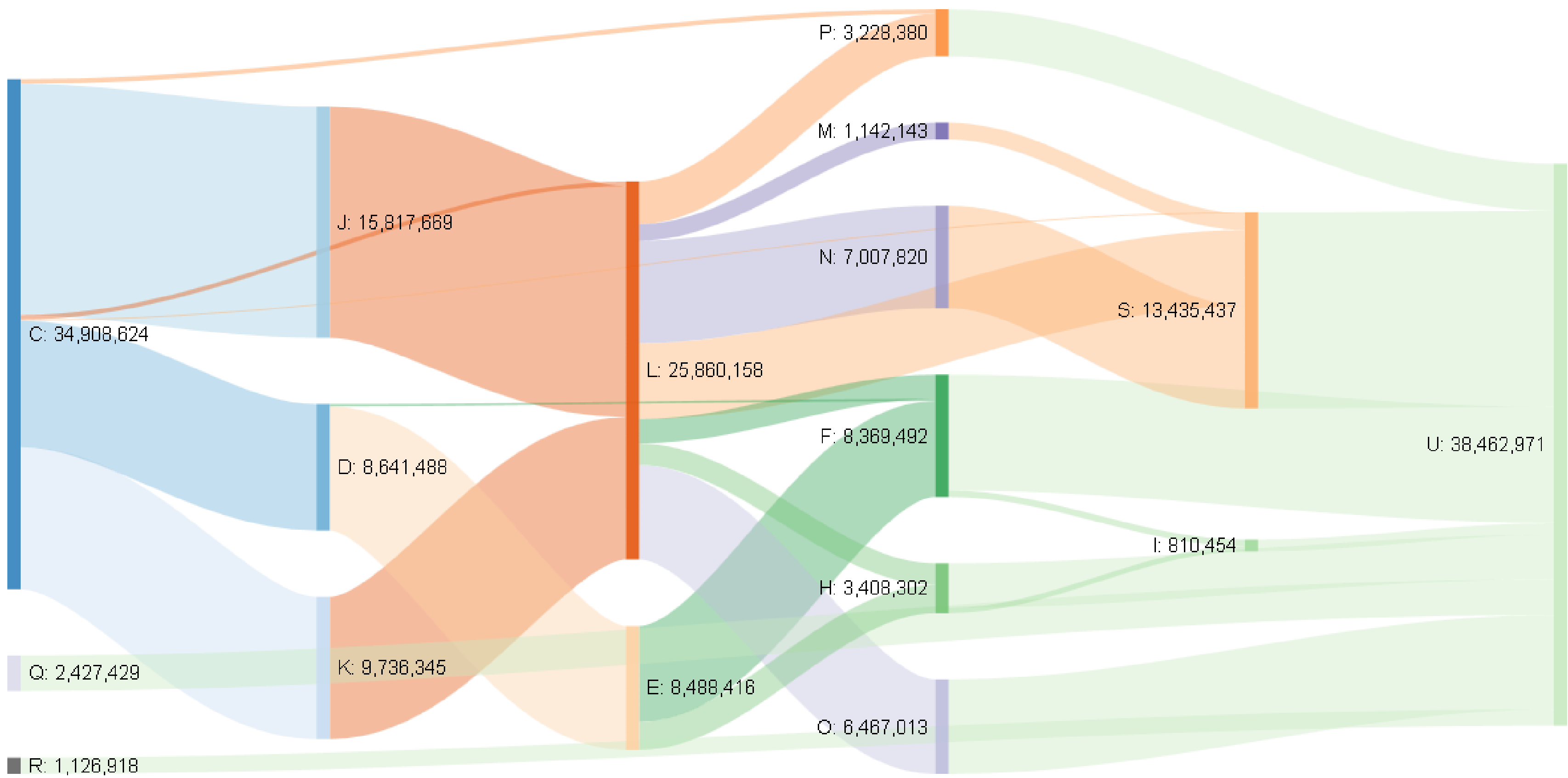


Figure 15 - Sankey Flow Chart[3]

Data input used in this flow chart creator can be viewed on Appendixes Table 42.

[3] Sankey Flow Chart - http://sankeymatic.com/

Figure 15 - Sankey Flow Chart was another tool implemented to give a greater knowledge and visualization of the flow of materials trough the manufacturing floor.

This chart has the advantage of easily show the flow between the different work stations and the weight of it. Some of the previous considerations could also be taken trough the analysis of this chart. Without the evaluation part of the project this chart can easily be the first layout to be feed to the next steps, the evaluation and improving part, giving a reasonable starting point for the iterations that follow.

One of the drawbacks of this chart is that for purposes of visualization it forces flow crisscrosses so that it can create a more pleasant and curvy chart. That can be pointed out in connections “D” and “K” and “O” and “F” for example, were it could be switched to prevent the crisscrosses.

3.2.2.4 Creation of a virtual image representation of workstations with proportionality to each other in excel

Given the relative measures and shapes of the workstations provided in Figure 16 it was need the creation of a virtual image representation of each one in excel.

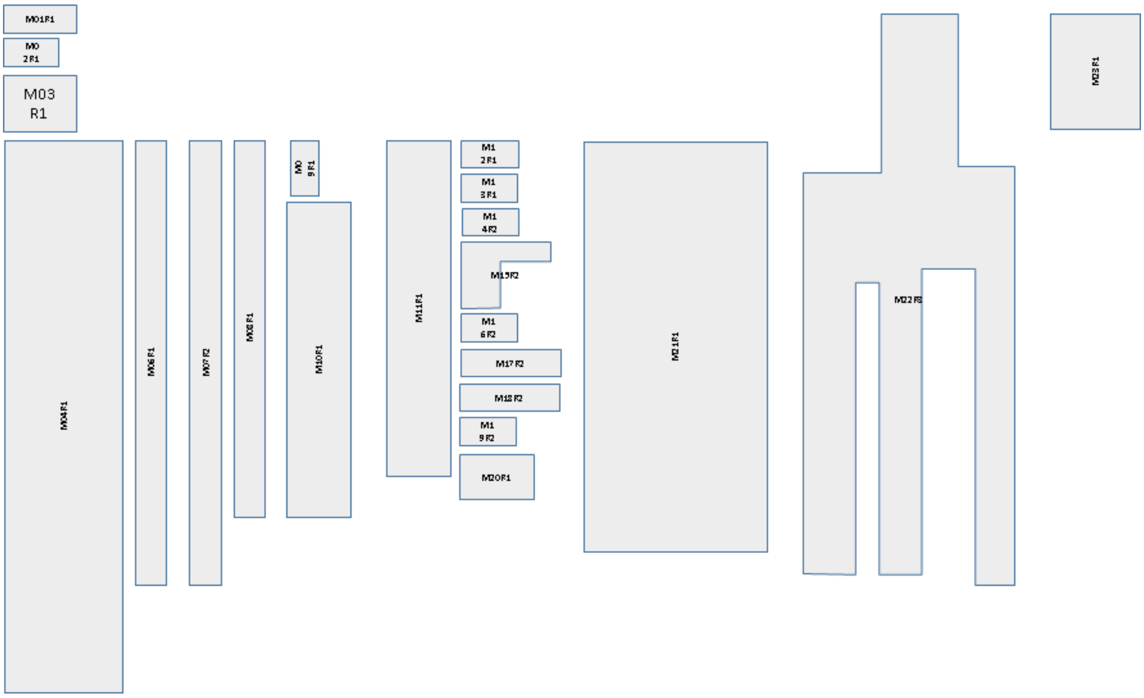


Figure 16 - Workstations relative measures

To create an automatic evaluation tool it were considered several requirements that could affect how the excel representation was created.

These requirements are:

1. Keep proportion and shapes as is.
2. Each workstation should be a multiple of equal and square individual excel cells
3. Should be represented entering and exiting points
4. Should have a maximum sum of with and length of 50 and 200 cells respectively because of future CRAFT developments.

To obtain the results based on the requirements it could just be made by multiplying a factor and rounding it to the closest integer. In this specific case that would work because of the relatively small initial measures. Even so, the calculation presented below works for all the cases, especially when the measures are greater than the expected excel representation.

Thus the results were calculated through a multiplying factor by the relative width and length.

The formulas behind this approach are as follows:

$$A = W_x * L_y \tag{5}$$

- A – Area
- W – Width
- L – Length

$$W_{relative} = \frac{w_{initial}}{\sum_{i=n}^{i=1} A_n} \tag{6}$$

- $W_{relative}$ – Relative width
- $W_{initial}$ – Initial width
- A_n – Area of the n^{th} workstation

Equation (6) is the same for relative length calculation with the respective changes.

$$W_{final} = W_{relative} * \alpha \tag{7}$$

- W_{final} – Final width round to the closest integer
- $W_{relative}$ – Relative width
- α – Multiplicative factor

To achieve the fourth goal, and given there were no direct formulas discovered, a process of trial and error was made and the results are presented in Figure 17.

#	Workstation	Length	With	Area	Relative Proportion		Factor x100		Factor x150		Factor x190		Factor x220		Workstation
		Y	X		Y	X	Y	X	Y	X	Y	X	Y	X	
1	M01R1	0,37	0,97	0,3589	0,004722	0,01238	0	1	1	2	1	2	1	3	A
2	M02R1	0,37	0,73	0,2701	0,004722	0,009317	0	1	1	1	1	2	1	2	B
3	M03R1	0,76	0,96	0,7296	0,0097	0,012252	1	1	1	2	2	2	2	3	C
4	M04R1	1,55	7,3	11,315	0,019782	0,093168	2	9	3	14	4	18	4	20	D
5	M05R1	1,55	7,3	11,315	0,019782	0,093168	2	9	3	14	4	18	4	20	E
6	M06R1	0,41	5,88	2,4108	0,005233	0,075045	1	8	1	11	1	14	1	17	F
7	M07R2	0,41	5,88	2,4108	0,005233	0,075045	1	8	1	11	1	14	1	17	G
8	M08R1	0,41	4,97	2,0377	0,005233	0,063431	1	6	1	10	1	12	1	14	H
9	M09R1	0,38	0,72	0,2736	0,00485	0,009189	0	1	1	1	1	2	1	2	I
10	M10R1	0,84	4,17	3,5028	0,010721	0,05322	1	5	2	8	2	10	2	12	J
11	M11R1	0,85	4,43	3,7655	0,010848	0,056539	1	6	2	8	2	11	2	12	K
12	M12R1	0,36	0,75	0,27	0,004595	0,009572	0	1	1	1	1	2	1	2	L
13	M13R1	0,36	0,75	0,27	0,004595	0,009572	0	1	1	1	1	2	1	2	M
14	M14R2	0,36	0,75	0,27	0,004595	0,009572	0	1	1	1	1	2	1	2	N
15	M15R2	0,87	1,19	1,0353	0,011104	0,015188	1	2	2	2	2	3	2	3	O
16	M16R2	0,36	0,75	0,27	0,004595	0,009572	0	1	1	1	1	2	1	2	P
17	M17R2	0,36	1,32	0,4752	0,004595	0,016847	0	2	1	3	1	3	1	4	Q
18	M18R2	0,36	1,32	0,4752	0,004595	0,016847	0	2	1	3	1	3	1	4	R
19	M19R2	0,36	0,75	0,27	0,004595	0,009572	0	1	1	1	1	2	1	2	S
20	M20R1	0,58	0,99	0,5742	0,007402	0,012635	1	1	1	2	1	2	2	3	T
21	M21R1	2,42	5,43	13,1406	0,030886	0,069301	3	7	5	10	6	13	7	15	U
22	M22R3	2,79	7,56	21,0924	0,035608	0,096486	4	10	5	14	7	18	8	21	V
23	M23R1	1,19	1,53	1,8207	0,015188	0,019527	2	2	2	3	3	4	3	4	W
	Total	18,27	66,4	78,3534	0,233174	0,847442	21	86	39	124	46	161	49	186	

Figure 17 - Workstation resize and transformation

Several trials were made, and several solutions discarded because of not fulfilling some or several requirements. Even so the last result highlighted in green was the one that grants the fulfilment of all of the goals previously set.

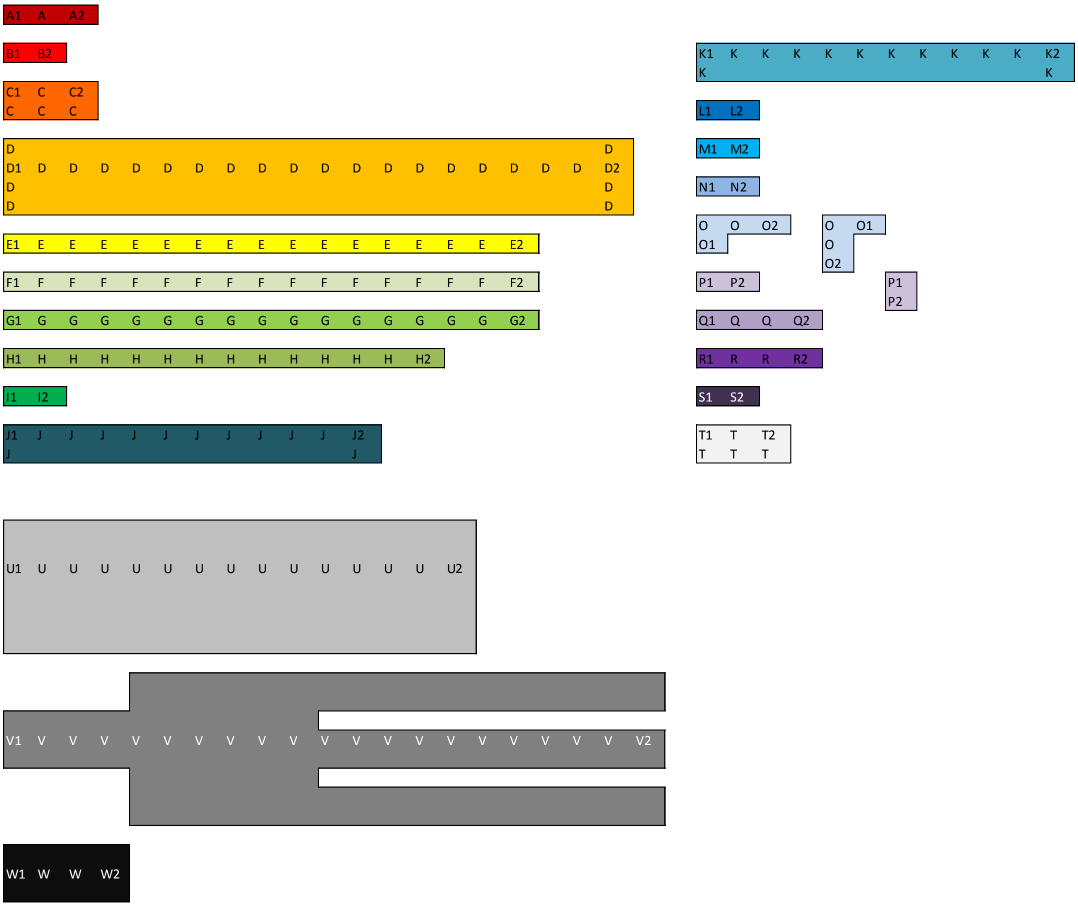


Figure 18 – Excel workstations representation

Figure 18 shows the converted departments created with multiples of one single square cell, with proportion and shapes relative to each other. For better visualization purposes each department was made with a different colour and the respective letter addressed earlier. The method used for calculation of entering and exit points was by representing those points by numbers, “1” for entering and “2” for exit.

It can also be pointed out how easily de departments can be rotated or inverted as shown by departments “O” and “P” double representation on the figure.

3.2.3 Layout Evaluation

Concerning the layout design several analytical approaches were studied, as previous mentioned before in the literature review, like the graph-based method and the pairwise exchange. But these methods have their own throwbacks especially when the problem is constituted by a great amount and very heterogeneous, regarding shapes and proportions, workstations and also, when specific entering and exiting points are defined.

Thus, it was needed an approach that could tackle these downsides.

Important questions to create an evaluation tool for the layout design problem:

- What to evaluate;
- How to evaluate.

3.2.3.1 What to evaluate

The heuristic approach usually takes one of these two methods, the distance-based scoring and the adjacency-based scoring. They were described before, but for argument purposes they are summed up here again.

Adjacency-based scoring objective is to maximize the sum of all weights, previously given by the relationships between the pair departments.

Distance based objective is to minimize the total cost of transporting materials among all departments in a facility, normally based on rectilinear distance from centroid to centroid.

Because of the data that was available, that could easily deliver the material quantity flow between departments, the problem in hands relates do the later approach, the distance-based one.

Distance-based scoring like pairwise exchange and CRAFT methods use the following equation for evaluation of the layouts.

$$\text{minTC} = \sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij} \times W_{ij} \times C_{ij} \tag{8}$$

TC is the Total cost;
D_{ij} is the distance from departments i to department j;
W_{ij} is the interdepartmental traffic from departments i to department j;
C_{ij} is the handling cost between departments i and department j.

3.2.3.2 How to evaluate

The first step of the evaluation process is to calculate how far the departments distance from each other. On that subject there are means of achieving this calculation depending on the type of layout expected and requirements. The rectilinear and Euclidian are two types of distance calculation that also relate to the point where the distance is measure being centroids the most used method.

3.2.3.2.1 Rectilinear

Distance between i and j:

$$D = |x_i + x_j| + |y_i + y_j| \quad (9)$$

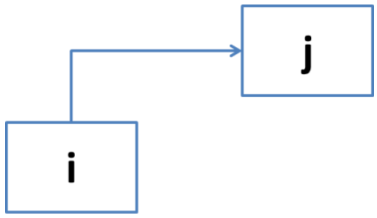


Figure 19 - Rectilinear distance

This method presents a calculation that tries to approximate to the real route of the materials from one department to another. Distance between two facilities is measured along path that is orthogonal to each other

3.2.3.2.2 Euclidian

Distance between i and j:

$$D = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad (10)$$

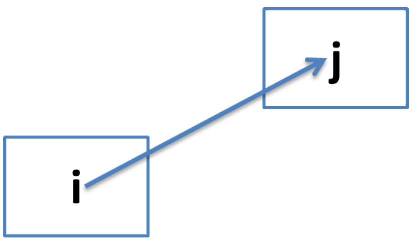


Figure 20 - Euclidian distance

Distance is measured along straight-line path between the two facilities.

3.2.3.2.3 Centroid

The centroid of a plane figure is the arithmetic mean position of all the points in the shape.

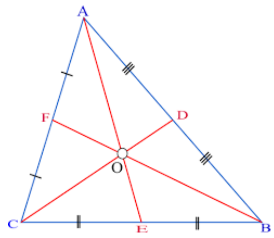


Figure 21 - Centroid example

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i * A_i}{\sum_{i=1}^{n} A_i} \quad (11)$$

Where $\bar{x}$ is the abscissa of the centroid and using the same equation with the respective changes would have $\bar{y}$ as the ordinate of the centroid, A_i is the area and x_i is the abscissa of the geometric decomposition of the figure.

3.2.3.2.4 Point of exit to entering point

One of the requirements brought by the analysis of the facility shapes and measures was the necessity of the calculation of the distances regarding the point of entering and exit of each department so that the results would approximate the real case. Thus an evaluation method would have to accomplish that. This is one of the great differences from the methods available.

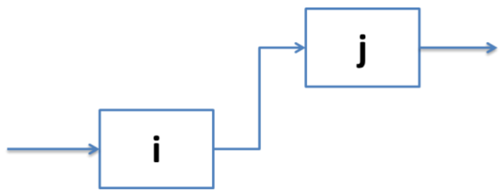


Figure 22 - Point of exit to entering point example

3.2.3.3 Layout evaluation tool

Given the department shapes created in the Figure 18 – Excel workstations representation, the equation and objective method of distance-based methods, the rectilinear distance calculation between the point of exit and entering of workstations, a excel based evaluation tool was created to aid the improvement process and account for all of the formulas and considerations taken previously. The following topics sum up the final tool.

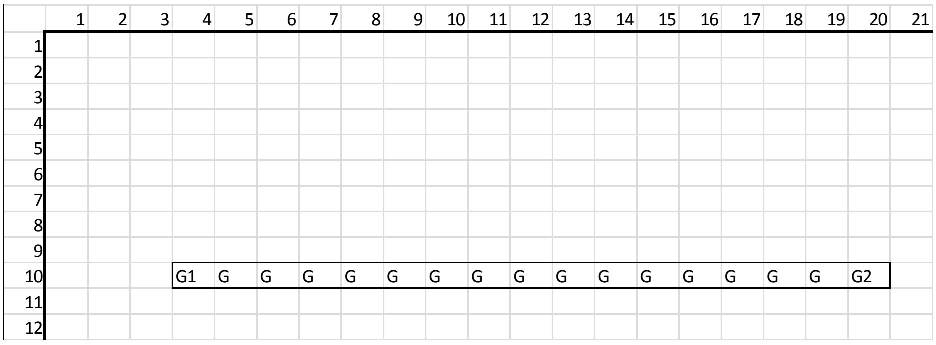


Figure 23 - Part of 2D map for layout calculation

Figure 23 presents part of the two dimensions excel map created for deployment of the layout figures calculated before. So each department is placed on the 2D map and then the distance is calculated using rectilinear equation and accounting the entering and exit points in each figure, represented in this case by the G1 and G2 letters respectively.

Table 20 – Part of Interdepartmental Flow Matrix

	A	B	C	D	E	F	G	H	I	J	K	L
A	0	0	0	0	0	0	0	0	0	0	0	0
B	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	8641488	0	0	0	0	0	15817669	9736345	306144
D	0	0	0	0	8488416	153072	0	0	0	0	0	0
E	0	0	0	0	0	6553643	0	1934773	0	0	0	0
F	0	0	0	0	0	0	0	0	445034	0	0	0
G	0	0	0	0	0	0	0	0	0	0	0	0
H	0	0	0	0	0	0	0	0	365420	0	0	0
I	0	0	0	0	0	0	0	0	0	0	0	0
J	0	0	0	0	0	0	0	0	0	0	0	15817669
K	0	0	0	0	0	0	0	0	0	0	0	9736345
L	0	0	0	0	0	1662777	0	1473529	0	0	0	0

Table 13 represents part of the global interdepartmental flow matrix which holds the total material movements between departments. Some departments as shown above with zero movements do not have material transit trough them respectively.

Table 21 - Part of Distance Calculation

	Distance
CD	6,0
CJ	2,0
CK	5,0
CL	15,0
CP	25,0
CS	23,0
DE	2,0
DF	20,0
DH	17,0
EF	2,0
EH	5,0
FI	4,0

Table 14 - Part of Distance Calculation shows part of the distance calculation with a filter that sorts with colors from greater value, red, to smaller green. Then with the respective distances and with the material flow from Table 13 – Part of Interdepartmental Flow Matrix it was calculated the cost matrix shown Table 15 - Part of the Cost matrix.

Table 22 - Part of the Cost matrix

Cost Matrix	A	B	C	D	E	F	G	H	I	J	K	L
A	0	0	0	0	0	0	0	0	0	0	0	0
B	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	34565952	0	0	0	0	0	15817669	29209035	3979872
D	0	0	0	0	8488416	2755296	0	0	0	0	0	0
E	0	0	0	0	0	6553643	0	9673865	0	0	0	0
F	0	0	0	0	0	0	0	0	7565578	0	0	0
G	0	0	0	0	0	0	0	0	0	0	0	0
H	0	0	0	0	0	0	0	0	5846720	0	0	0
I	0	0	0	0	0	0	0	0	0	0	0	0
J	0	0	0	0	0	0	0	0	0	0	0	15817669
K	0	0	0	0	0	0	0	0	0	0	0	29209035
L	0	0	0	0	0	41569425	0	30944109	0	0	0	0

Table 15 exemplifies part of the global cost matrix which represents the calculation of the equation (8) without the final sum of the total cost of all departments. Each cell reflects the total movement between department plus de distance plus the cost of movement.

The final results are then presented in Table 16 so that a comparison of choices made can be evaluated. These results represent the final calculation equation (8).

Table 23 - Iteration Total Cost

Iteration	Total Cost
8	657346365
7	657346365
6	670313629
5	727871931
4	780076095
3	1116195677
2	1091071339
1	1308188800

3.2.4 Layout Improvement

Layout improvement, defines the iterative process taken to make incremental and improving changes through the information gathered from the layout evaluation based on intuition, judgment and experience learning.

The steps taken in this method were:

- Create the first layout by choosing departments with the greater interdepartmental flow and place them together on the 2D map. Go through Table 12 – Filtered interdepartmental flow till the end and place all the departments;
- Check total cost for the existing layout;
- For each iteration evaluate all feasible exchanges in the locations of department pairs;
- Select the pair that results in the largest reduction in total cost;
- With intuition, judgment and experience learning practice do new experiments;
- Stop when no visible exchange can be made that could diminish the total cost and the the current iteration is worse than previous.

3.2.4.1 First Iteration Example

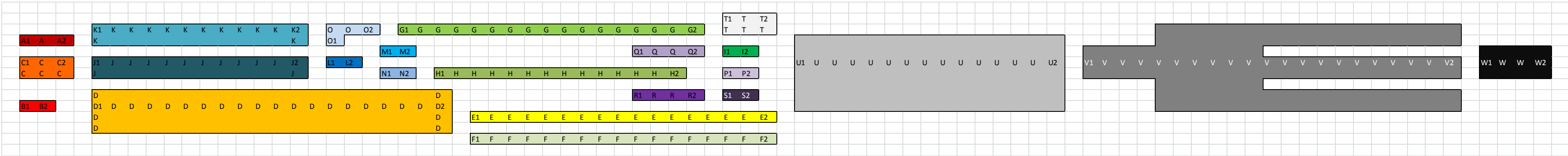


Figure 24 - First Iteration

Figure 24 denotes the first iteration. It serves as a first step to the following chapter, results analysis were the next iterations will be discussed. For the layout construction it was added one cell space around each department representing for example material flow paths or the real scenario in a production floor.

Cost Matrix	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	34565952	0	0	0	0	0	15817669	29209035	3979872	0	0	0	6511640	0	0	1546524	0	0
D	0	0	0	0	8488416	3979872	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E	0	0	0	0	0	281806649	0	83195239	0	0	0	0	0	0	0	0	0	0	0	0	0
F	0	0	0	0	0	0	0	0	2225170	0	0	0	0	0	0	0	0	0	0	0	15848916
G	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H	0	0	0	0	0	0	0	0	1461680	0	0	0	0	0	0	0	0	0	0	0	9128646
I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3241816
J	0	0	0	0	0	0	0	0	0	0	0	15817669	0	0	0	0	0	0	0	0	0
K	0	0	0	0	0	0	0	0	0	0	0	29209035	0	0	0	0	0	0	0	0	0
L	0	0	0	0	0	28267209	0	25049993	0	0	0	0	2284286	7007820	6467013	17416788	0	0	26020390	0	0
M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4568572	0	0
N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35039100	0	0
O	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19401039
P	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6456760
Q	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7282287
R	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4507672
S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13435437
T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 24 - First Iteration Cost Matrix

Table 17 shows the cost matrix first iteration. For analysis purposes it was applied a filter, the red values represent a greater cost, where a light yellow represents a minor cost.

Iteration	Total Cost
1	749238166

Table 25 - First Iteration Total Cost

Table 18 represents the final result of equation (8) which will serve for comparison evaluation of the different iterations. The objective will be the reduction of the total cost.

Table 26 - First Iteration Distance Calculation

	Distance
CJ	2,0
JL	2,0
SU	6,0
CK	5,0
KL	5,0
CD	6,0
DE	3,0
FU	9,0
LN	3,0
NS	20,0
EF	18,0
LO	3,0
OU	27,0
LS	24,0
PU	4,0
HU	8,0
LP	22,0
QU	31,0
EH	22,0
LF	14,0
LH	6,0
LM	3,0
MS	22,0
RU	9,0
IU	4,0
FI	10,0
HI	5,0
CP	38,0
CL	15,0
DF	5,0
CS	40,0
DH	3,0
EH	22,0
MP	20,0

Table 19 denotes the rectilinear distance calculation between the exit point of one station and the entering point of another. Because in this case study the cost is the same for every movement and this table is ordered by great amount of material movement, the reduction process can focus partly on it.

3.3 AnyLogic Simulation Software

For this dissertation development it was previously defined Anylogic software [19] as the platform for computational model simulation. This topic presents an overview of the software used in the project and its main tools and characteristics.

Figure 25 - AnyLogic

AnyLogic software is a tool supporting the most common simulation methods nowadays, namely System Dynamic, Process-Centric/Discrete Events and Agent based modulation, which can be used simultaneously and combined.

The application areas are quite diverse and can be highlighted the following:

- Supply Chains and logistics
- Healthcare and Pharma
- Marketing and competition
- Manufacturing and production
- Pedestrian flows: airports, stations, malls
- Transportation and warehousing
- Project and asset management
- Business Processes and service systems
- Railroads
- Military and defence
- IT and telecom
- Strategic planning and management
- Social processes

According to Grigoryev in the book "AnyLogic 7 in Three Days" [69] modeling by discrete events requires a modeler who thinks in the modeling system as a process, an operation sequence made by agents. This modulation can include operations that include delays, services by several features, selection of process branches, divisions and many others. As long as the agents compete for limited resources and can suffer delays, the rows will make part of almost all discrete events models.

The agents defined were originally called transitions in General Purpose Simulation System (GPSS) or entities in other simulation software's. They can represent clients, parts, products, computation transactions, vehicles, tasks, projects, ideas among others. While resources on the other hand represent staff, operators, workers, servers, CPU's, computer memories, equipment and transport.

In this software model is graphically specified as a process flowchart whereas blocks represent operations. The flowchart typically starts with a “source” type of block that generates the agents and inserts them in the process and ends with a “sink” type of block that removes them.

The service time and the agents arrival is typically stochastic, and because they are generated from a probability distribution, the discrete event models are themselves also stochastic.

In practical terms, results from the need of the model to run certain time or complete a set of replicates in order to produce significant results.

The author ends referring that typically results of a simulation model by discrete events can have as exits the resource utilization rate, time spent within the system or part by an agent, waiting times, queue size, system throughput and also bottlenecks.

3.3.1 User Interface

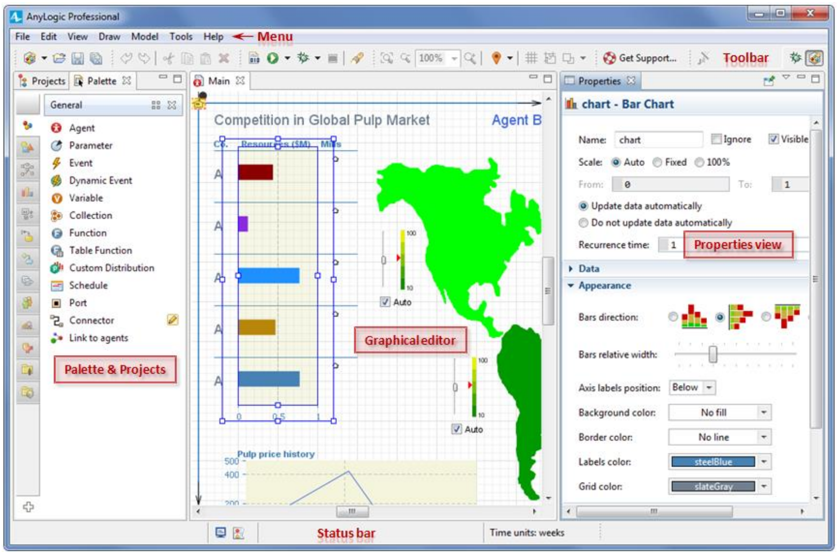


Figure 26 - AnyLogic User Interface

At the very top of the window the menu is located, under the menu - the toolbar providing the easy access to the most frequently used commands. At the bottom you can see the status bar.

By default the following components are shown in the workspace:

- Graphical editor - The place to edit graphical diagrams of agents and experiments.
- Projects view - Provides access to AnyLogic models currently opened in the workspace. The workspace tree provides easy navigation throughout the models.
- Palette view - Provides the list of model elements grouped by categories in a number of stencils (palettes).
- Properties view - Allows viewing and modifying the properties of currently selected model item(s).
- Problems view - Displays errors found during model development and compilation.

3.3.1.1 Pallete

The Palette view provides the list of graphical model elements grouped by categories in a number of stencils (palettes) and it is the place to find any AnyLogic graphical element to be add onto a graphical diagram of some agent class or experiment.

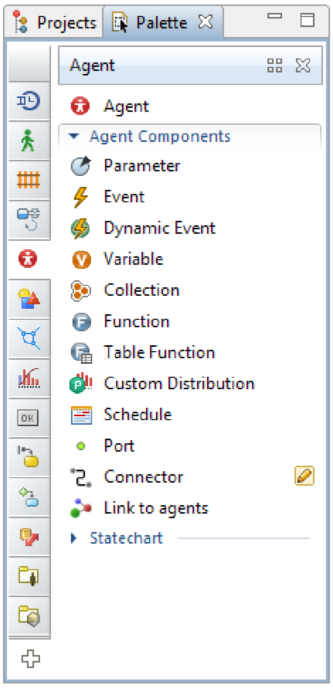


Figure 27 - AnyLogic Pallete

The Palette view consists of a number of stencils:

- Agent - The stencil contains elements for defining dynamics of the model, its structure and data.
- Presentation - The stencil contains shapes (line, oval, rectangle, polyline, curve, etc.), that you can use to draw presentations and 3D animations of your models and also a set of elements (3D window, camera, light) required to construct 3D animation scene.
- System Dynamics - The stencil contains elements frequently used by System Dynamics modellers.
- State-chart - The stencil contains elements of state-charts.
- Action-chart - The stencil contains blocks of action-charts - structured block charts allowing defining algorithms graphically.
- Analysis - The stencil contains elements, used for collecting, viewing and analysing output data.
- Controls - The stencil contains controls (button, slider, checkbox, etc.) providing ability for creating interactive active object presentations.
- Connectivity - The stencil contains tools for database connectivity.
- Pictures - The stencil contains a set of pictures of frequently modelled objects.
- 3D Objects - The stencil contains a set of 3D images of frequently modelled objects.

3.3.1.2 Properties

The Properties view is used to view and modify the properties of a currently selected model item(s). When something is selected the Properties view displays the properties of the selection.

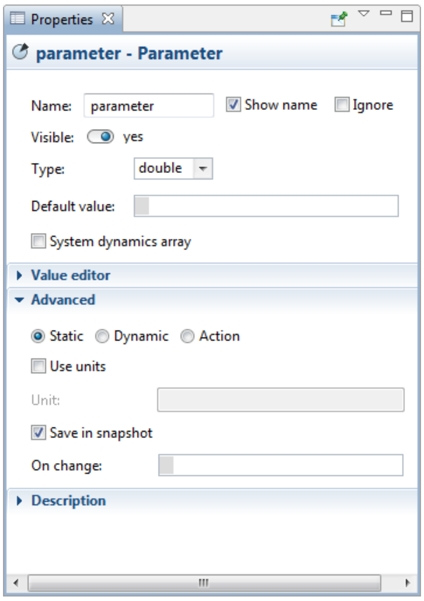
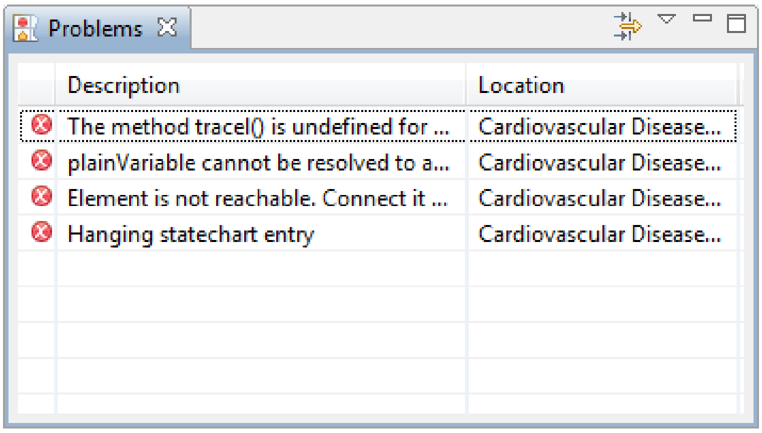


Figure 28 - Item Properties

The Properties view contains several sections. Every section contains controls such as edit boxes, check boxes, buttons, etc., used to view and modify properties. The number of pages and their appearance depend on the type of a selected object.

3.3.1.3 Problems

AnyLogic supports on-the-fly checking of types, parameters, and diagram syntax. AnyLogic may automatically detect some problems or errors as the model is being developed. The errors found during code generation and/or compilation are displayed in AnyLogic Problems view. For each error, the Problems view displays description and location.



Depending on the error, opening it may result in displaying different views. If, for example, it is a graphical error, the corresponding diagram is opened in the graphical editor with invalid shapes highlighted.

The Problems view displays information about problems of two types: errors and warnings.

- Error - a critical problem that makes the model non-working and should be necessarily fixed.
- Warning - information about some non-critical issue that may potentially lead to some problems or just an advice how to optimize the implementation (e.g. information about use of deprecated function). Warnings do not to prevent you from running the model.

3.3.1.4 Agents

According to Grigoryev in the book "AnyLogic 7 in Three Days" [69] modulation by discrete events requires a modulator who thinks in the modulating system as a process, an operation sequence made by agents. This modulation can include operations that include delays, services by several features, selection of process branches, divisions and many others. As long as the agents compete for limited resources and can suffer delays, the rows will make part of almost all discrete events models.

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The service time and the agents' arrival are typically stochastic, and because they are generated from a probability distribution, the discrete event models are themselves also stochastic.

In practical terms, results from the need of the model to run certain time or complete a set of replicates in order to produce significant results.

The author ends referring that typically results of a simulation model by discrete events can have as exits the resource utilization rate, time spent within the system or part by an agent, waiting times, queue size, system throughput and also bottlenecks.

Within an agent it can define variables, events, state-charts, system dynamics stock and flow diagrams, you can also embed other agents, add process flowcharts and as many types in the model as there are different types of agents.

Design of an agent typically starts with identifying its attributes, behavior and interface with the external world. In case of large number of agents with dynamic connections (such as social networks) agents can communicate by calling functions.

The agent internal state and behavior can be implemented in a number of ways. The state of the agent can be represented by a number of variables, by the state-chart state, etc. The behavior can be so to say passive (e.g. there are agents that only react to message arrivals or to function calls and do not have their own timing), or active, when internal dynamics (timeouts or system dynamics processes) of the agent causes it to act. In the latter case agents most probably would have event and/or state-chart objects inside.

3.3.1.5 Events

Event is the simplest way to schedule some action in the model. Thus, events are commonly used to model delays and timeouts.

There are three types of events:

1. Timeout triggered event. It is used when an action is schedule at some particular moment of time (or some particular date).The event occurs exactly in timeout time after it is started. Timeout triggered event has even more features: you can specify that it expires either once or cyclically, or is fully controlled by the user.
2. Condition triggered event is used to monitor a certain condition and execute an action when this condition becomes true.
3. Rate triggered event is used to model a stream of independent events (Poisson stream). It is frequently needed to model arrivals: e.g. customer arrivals in queuing systems, transaction arrivals in server-based network models, etc.

3.3.1.6 Variables

Agent can contain variables. Variables are generally used to store the results of model simulation or to model some data units or object characteristics, changing over time. AnyLogic supports two types of variables – variables and collections.

Collections are used for defining data objects that group multiple elements into a single unit.

Variable is a simple variable of an arbitrary scalar type or Java class. It always has some value assigned.

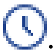
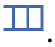
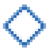
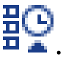
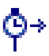
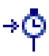
Java variables can be declared in the Additional class code field in the Advanced Java properties section of the agent type. Variables declared in the code can also be accessed within this object, but defining them visually using variables is much more efficient.

Alike other simulation tools AnyLogic supports variables of primitive types: double, integer, Boolean, but only AnyLogic gives infinite possibilities in defining data units by supporting variables of any Java classes.

3.3.2 Process Modelling Library Blocks

Agents contained in the Process Modelling Library are the building blocks that can be used to construct flowcharts. As usual, objects generate agents, control agent flow, process agents, work with resources, and transport agents. In this reference guide, they are described in the following categories:

Table 27 - Process Modelling Library Blocks

Library Blocks	Description
	Source – Generates agents.
	Sink – Disposes incoming agents.
	Delay – Delays agents by the specified delay time
	Queue – Stores agents in the specified order
	SelectOutput – Forwards the agent to one of the output ports depending on the condition.
	SelectOutput5 – Routes the incoming agents to one of the five output ports depending on (probabilistic or deterministic) conditions.
	Hold – Blocks/unblocks the agent flow.
	Assembler – Assembles a certain number of agents from several sources (5 or less) into a single agent
	Conveyor – Moves agents at a certain speed, preserving order and space between them.
	ResourcePool – Provides resource units that are seized and released by agents.
	Seize – Seizes the number of units of the specified resource required by the agent.
	Release – Releases resource units previously seized by the agent.
	Service – Seizes resource units for the agent, delays it, and releases the seized units
	Enter – Inserts agents created elsewhere into the flowchart.
	Exit – Accepts incoming agents
	TimeMeasureStart – TimeMeasureStart as well as TimeMeasureEnd compose a pair of objects measuring the time the agents spend between them, such as "time in system", "length of stay", etc. This object remembers the time when an agent goes through.
	TimeMeasureEnd – TimeMeasureEnd as well as TimeMeasureStart compose a pair of objects measuring the time the agents spend between them. For each incoming agent this object measures the time it spent since it has been through one of the corresponding TimeMeasureStart objects.

3.4 Simulation Modeling

This topic will explain the simulation model construction, the steps taken and the major reflections taken.

Previously it were studied several production tools and methods regarding their capability to be simulated using discrete events, afterwards, and given these conclusions it was developed a facility layout method to aid the determination of good solutions. Because of the raised importance in this project of layout determination and the analysis obtained of the capability of buffer simulation and their benefits it was considered a major improvement if the simulation could aid to achieve a better result and more realistic layout.

Recalling: "The determination of buffer size also has a bearing on the performance characteristics such as productivity, flexibility, and space utilization for a manufacturing system."

Thus it was believed that the simulation of the case study could point out the need for additional factory floor space to account the need for buffers, and that this assessment would affect the final layout solution.

Therefore, the following topics will address the construction of a tool to calculate buffer size given a typical demand of products input.

3.4.1 System requirements

The objective is to develop a simulation model capable of running the data input from a case study to obtain the expected size of the workstation buffers. Therefor providing further information relative to the space needed so that the layout initial solution can be improved in a greater realistic way.

3.4.1.1.1 Functional Requirements

- Determine buffer size for each department

3.4.1.1.2 Non-Functional Requirements

- Use AnyLogic Simulation Software
- Run simulation in less than 5 minutes
- Use case study data as input
- Extract results

3.4.2 Model Creation

Given the system requisites and objectives, this topic will address the major steps taken to create a simulation model that can respond to the needs.

3.4.2.1 Buffer Simulation Model Flowchart

For better interpretation of the simulation process it was developed a flowchart.

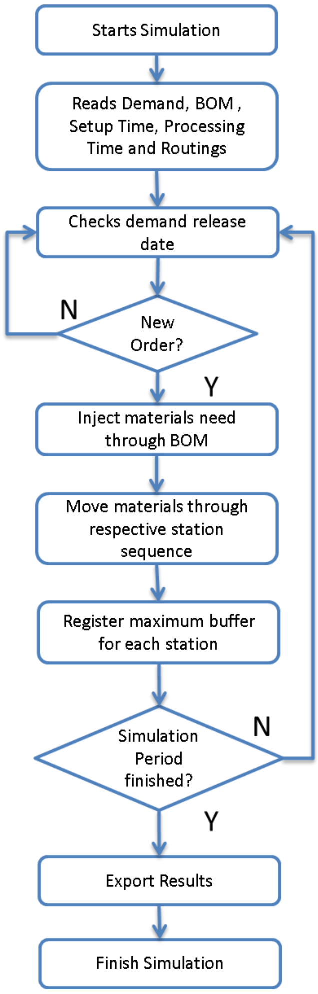


Figure 29 - Buffer Simulation Model Flowchart

Figure 29 represents the simulation model logic behind the implementation. The simulation starts with the load of the information from the excel sheet, and stored in several variables and collections like the demand, the bill of materials, the routings, the processing times and other information. Then, given that the demand happens at a specific frequency, an event is triggered every day at that specific time, searching for the release date of the orders. Whenever an order has that specific release date, the materials are injected with the respective quantity and type given by the bill of materials from the relation with the expected final product that needs them.

Every material follows the specific route of machine sequences until the end, and for every different type, the respective processing times are applied. The simulation ends when the period/time given for the simulation, in this case 1 year, finishes.

3.4.2.2 Data Input

Table 21 shows the partial component demand. Where "idDemand" is the unique order identifying number; "idComponent" refers to product type; "releaseDate" refers to the date arrival of the order; "Total Production" is the amount of products needed to fulfil the order. Other tables exist but were not used in this simulation.

There are 68 types of product with an annual demand of 357.010.

Table 28 - Partial Component Demand

idDemand	idComponent	amount	lotsize	Priority	releaseDate	Total Production
1	274	1	1789	0	05-01-2015 00:00	1789
2	279	1	1777	0	05-01-2015 00:00	1777
3	284	1	1334	0	05-01-2015 00:00	1334
---	---	---	---	---	---	---
358	295	1	94	0	20-02-2015 00:00	94

This model for the buffer sizing calculation implements a push production that pushes orders in the system that pushes products, which in the end push materials. Even though later it tried a pull system, this was the best way to create a discrete event that released a waterfall of functions and creations of agents/materials.

Bill of materials is a list of raw materials or unassembled parts and quantities that constitute each product.

Table 29 - Bill of Materials

idProduct	idMaterial	materialDescription	BOM multiplier
232	69	Material_69	2
232	70	Material_70	2
233	13	Material_13	2
233	14	Material_14	2
---	---	---	---
299	77	Material_77	2
299	67	Material_67	2
299	50	Material_50	1
299	17	Material_17	1

In Table 22, "idProduct" stands for the product type, "idMaterial" for the material type and "BOM multiplier" for the quantity of each material to compose a product.

When a product enters the model a function creates a population of materials based on the "*productType*", bill of materials and quantity needed, parameters loaded from product variables, the BOM from BOM sheet and the routing from the materials sheet.

This way we create a need for materials in the production line.

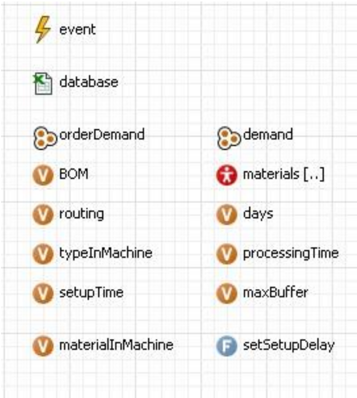


Figure 30 - AnyLogic Model Variables

Routings represent several important factors that aid to give reality to the model, like the sequence of workstations, the setup time, the processing time and the alternatives.

Table 30 – Partial Routing Sequence

idMaterial	Alt	idInputMachine	idMachineString	idMachineStringAlt	ProcessingTime	ProcessingTimeAlt
1	0	M03R1			0,0023	
1	0	M11R1			0,0176	
1	0	M12R1			0	
1	1	M14R2	M14R2	M13R1	0,0526	0,1754
1	0	M19R2			0	
1	0	M21R1			0	
1	0	Sink1			0	
---	---	---	---	---	---	---
256	1	M17R2	M17R2	M18R2	0,3922	0,3509
256	0	M21R1			0,0283	
256	0	Sink1			0	

In Table 23, “idMaterial” represents the material type, “Alt”is a variable that states that there is a workstation alternative, “idInputMachine” represents a string sequence of workstations, “idMachineStringAlt” represents the workstation alternative sequence, “ProcessingTime” the time that each workstation takes to process a specific material and “ProcessingTimeAlt” the time that the alternative workstation takes to process a specific material.

Given the need for easier and fast access, issue addressed afterwards, this table was used to construct two specific excel sheets, one for the routing Table 26, and another for the processing time matrix Table 24.

Table 31 – Partial Workstation Processing Time by Material Type

materialType	A	B	C	D	E	F	G	---	Y
1	0,00000	0,00000	0,00230	0,00000	0,00000	0,00000	0,00000	---	0,00000
2	0,00000	0,00000	0,00230	0,00000	0,00000	0,00000	0,00000	---	0,00000
3	0,00000	0,00000	0,00070	0,00000	0,00000	0,00000	0,00000	---	0,00000
4	0,00000	0,00000	0,00330	0,00000	0,00000	0,00000	0,00000	---	0,00000
---	---	---	---	---	---	---	---	---	---
256	0,00000	0,00000	0,00000	0,00000	0,00000	256	0,00000		,00000

Table 24 was then loaded to a java integer matrix to allow rapid access avoiding for cycles.

Table 32 - Setup Time

idMachine Number	MachineId	Resource	Workstation Name	Machine setup times	WorkCentre capacity
1	A	M01R1	Cutting	0,00	0,00
2	B	M02R1	Coating	0,00	0,00
3	C	M03R1	Sawing	1,00	1,00
4	D	M04R1	Wrapping	15,00	1,00
5	E	M05R1	Cross cutting	10,00	1,00
-	-	-	-	-	-
25	Y	Sink		0,00	0,00

In Table 25, "MachineId"represents the letter identifier as mentioned above, "Machine Setup Time" represents the time taken for setup of the workstation whenever a different material arrives to it, "WorkCentre Capacity" represents how many materials at once the machine can handle.

Table 33 - Material Workstation Sequence

materialType	materialRouting
1	CKLNSUY
2	CKLNSUY
---	---
256	QUY

For the material routing, or workstation sequence, given the number of workstations were equal to the number of letters of the alphabet, the approach was to identify each machine by a letter and concatenate it into a string. Thus for a specific material it was passed in the beginning of the model a string variable with the routing. This was created to facilitate and increase the speed of the routing sequence determination.

Then using a select output AnyLogic block the routing was determined with a java function checking if *materialRouting* parameter contains the machine station name.

```
agent.materialRouting.contains("F")
```

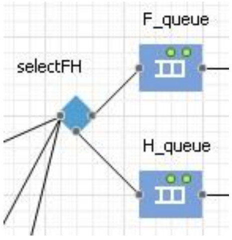


Figure 31 - Selection of the routing Sequence

3.4.2.3 Development of WorkStation Logic

For each department it was developed a set of blocks that could model and approximate the real behaviour of the workstations and also measure the maximum buffer.

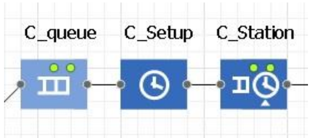


Figure 32 - Workstation Example

Figure 32 represents the logic of one workstation, the first block is an Anylogic queue, the second a delay and the third a service.

The queue block represents the buffer, each material waits there for its turn to be processed in the following blocks. The delay block represents the setup time, whenever a different type of material than the last one processed in the service block arrives, the setup is triggered and the respective delay/setup time is started.

The service block represents several internal blocks, the delay block which simulates the processing time for each material type, a seize and a release block with relates to the respective resource. Essentially a resource for each machine is created with the respective capacity, and then connected to a service block. The seize and release of resources allows a deeper analysis, in this case the collection of utilization statistics.

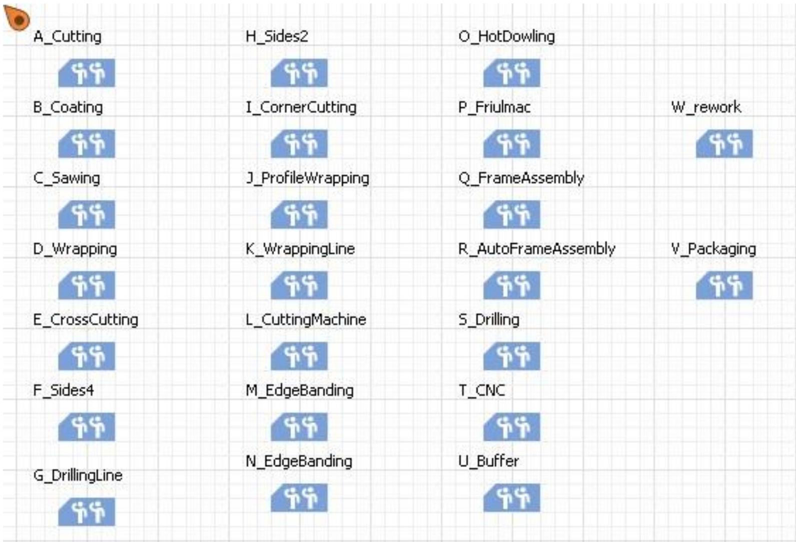


Figure 33 - AnyLogic Workstations

Figure 33 represents the resource blocks created to model the workstations allowing has previous mentioned additional collection of statistics.

3.4.2.4 Buffer Calculation

For the maximum buffer calculation in each department it was created an array to store the current maximum size. Whenever a material arrived to the each queue block, a function checked if the current size was greater than the stored one, this way only updating when the buffer size reached a new maximum. The function is represented in Figure 34.

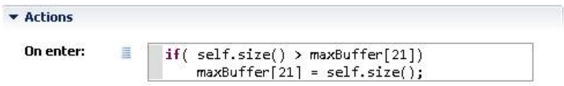


Figure 34 - Maximum Buffer Function

Figure 35 demonstrates the printing function of the results needed to the console.

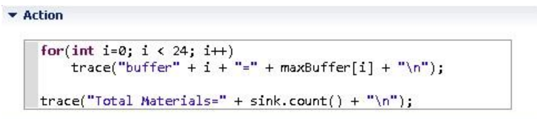


Figure 35 - Print Buffer Function

3.4.3 Final Buffer Simulation Model

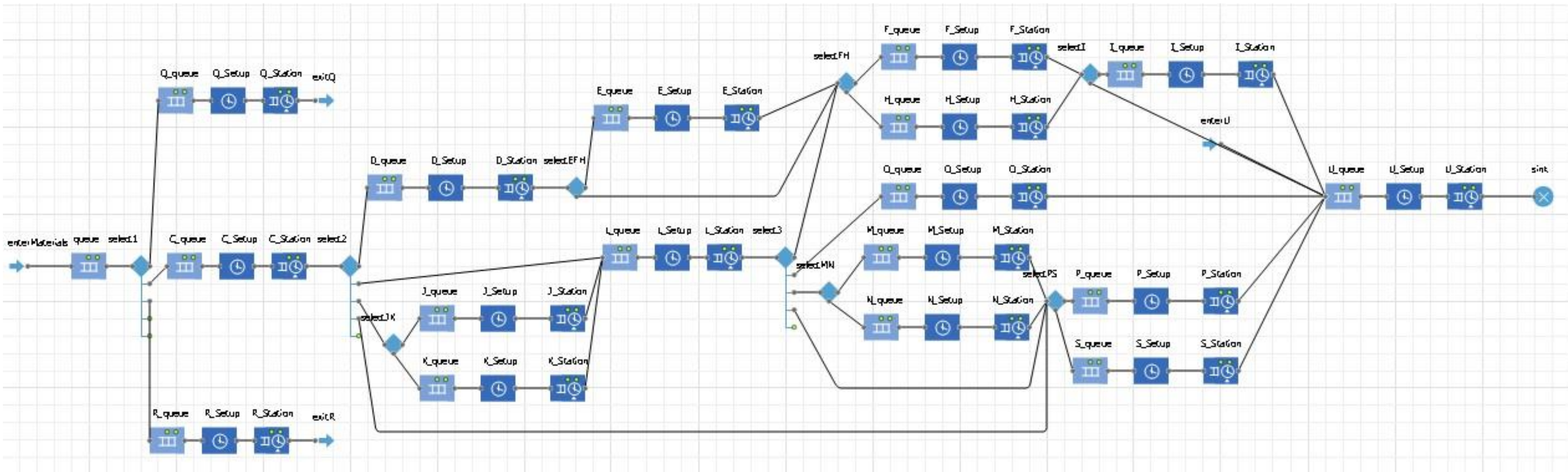


Figure 36 - Buffer Simulation Model

Figure 36 shows the final result of the buffer simulation model. This representation was build using the interdepartmental flow graph from Figure 13, and implemented with the necessary blocks and additional code has stated above to fulfil the system requirements.

The logic behind it was shown in Figure 29 - Buffer Simulation Model Flowchart.

Essentially, the model waits for the arrival of product demand, and then being a push model, it injects the respective need of materials to assemble the product through the bill of materials. After, each set of materials enters the model using a enter block, and flows to the respective workstation sequence, being processed accordingly, following the convergence to the final workstation and exit from the model.

Chapter 4

Results analysis

This chapter presents the relevant results obtained through the project. It is divided in 3 major topics. The first addresses the results from the facility layout method presented in the previous chapter. Secondly it is examined the buffer simulation results followed by the aggregate analysis of the 2. This analysis will verify what changes need to be done to the analytical facility layout approach because of the simulation conclusions, thus improving the final layout.

4.1 Facility Layout Results Analysis

This topic displays the major results from the facility layout method developed before. It is itself divided in 3 parts. Firstly it is shown the improving process through several iterations, followed by a comparison of results to another method, the CRAFT, in part 2. Lastly a global result analysis is made.

4.1.1 Iteration Results

Because of future layout improve using the results from the buffer simulation that follows, this topic will address the layout process more briefly. This analysis starts with the first iteration solution, and then using the graphs, the tables, and the steps defined previously along with intuition, judgment and experience learning practice, new experiments/iterations are created.

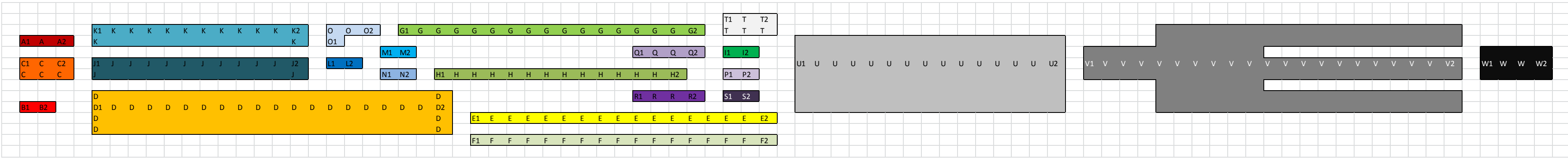


Figure 37 - First Iteration

Figure 37 denotes the first iteration. For the layout construction it was added one cell space around each department representing for example material flow paths or the real scenario in a production floor. This layout was constructed has previous mentioned in Chapter 3 using the interdepartmental flow information.

Cost Matrix	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	34565952	0	0	0	0	0	15817669	29209035	3979872	0	0	0	6511640	0	0	1546524	0	0
D	0	0	0	0	8488416	3979872	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E	0	0	0	0	0	281806649	0	83195239	0	0	0	0	0	0	0	0	0	0	0	0	0
F	0	0	0	0	0	0	0	0	2225170	0	0	0	0	0	0	0	0	0	0	0	15848916
G	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H	0	0	0	0	0	0	0	0	1461680	0	0	0	0	0	0	0	0	0	0	0	9128646
I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3241816
J	0	0	0	0	0	0	0	0	0	0	0	15817669	0	0	0	0	0	0	0	0	0
K	0	0	0	0	0	0	0	0	0	0	0	29209035	0	0	0	0	0	0	0	0	0
L	0	0	0	0	0	28267209	0	25049993	0	0	0	0	2284286	7007820	6467013	17416788	0	0	26020390	0	0
M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4568572	0	0
N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35039100	0	0
O	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19401039
P	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6456760
Q	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7282287
R	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4507672
S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13435437
T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 34 - First Iteration Cost Matrix

Table 27 shows the cost matrix first iteration. For analysis purposes it was applied a filter, the red values represent a greater cost, where a light yellow represents a minor cost.

Iteration	Total Cost
1	1308188800

Table 35 - First Iteration Total Cost

Table 28 represents the final result of equation (8) which will serve for comparison evaluation of the different iterations. The objective will be the reduction of the total cost.

Table 36 - First Iteration Distance Calculation

	Distance
CJ	2,0
JL	2,0
SU	6,0
CK	5,0
KL	5,0
CD	6,0
DE	3,0
FU	9,0
LN	3,0
NS	20,0
EF	18,0
LO	3,0
OU	27,0
LS	24,0
PU	4,0
HU	8,0
LP	22,0
QU	31,0
EH	22,0
LF	14,0
LH	6,0
LM	3,0
MS	22,0
RU	9,0
IU	4,0
FI	10,0
HI	5,0
CP	38,0
CL	15,0
DF	5,0
CS	40,0
DH	3,0
EH	22,0
MP	20,0

Table 29 denotes the rectilinear distance calculation between the exit point of one station and the entering point of another.

The main objective of this method is to minimize the equation (8) which relates the distance, the interdepartmental traffic and the the handling cost of those movements. Given that there was no information regarding different costs in different movements it was considered that the cost was the same for all the movements. Thus only two factors of the equation remain the interdepartmental traffic and the distance. Because Table 19 is ordered from greater amount of traffic between two departments, the less amount of distance from the top results in a smaller total cost. So one of the best objectives is to get the top departments as close as possible they can be.

Therefore, it can be observed that with the first iteration the top 3 connections, “CJ” and “JL” are as close they can be.

Because of “CJ” and “JL” connections “CK”, “KL” and “CD” apparently cannot be any closer. But “DE”, “SU”, “NS” and “EF” can be closer by arranging the layout.

As affirmed because another layout improving process with the results from buffer simulation is needed, this analysis is brief. Thus the table that follows illustrates 5 iterations.

Table 37 - Layout Iterations

Iteration 1	Distance	Iteration 2	Distance	Iteration 3	Distance	Iteration 4	Distance	Iteration 5	Distance
CJ	2,0	CJ	2,0	CJ	2,0	CJ	2,0	CJ	2,0
JL	2,0	JL	2,0	JL	2,0	JL	2,0	JL	2,0
SU	6,0	SU	2,0	SU	2,0	SU	2,0	SU	2,0
CK	5,0	CK	5,0	CK	5,0	CK	5,0	CK	5,0
KL	5,0	KL	5,0	KL	5,0	KL	5,0	KL	5,0
CD	6,0	CD	12,0	CD	6,0	CD	6,0	CD	6,0
DE	3,0	DE	3,0	DE	2,0	DE	2,0	DE	2,0
FU	9,0	FU	7,0	FU	5,0	FU	5,0	FU	5,0
LN	3,0	LN	3,0	LN	2,0	LN	3,0	LN	4,0
NS	20,0	NS	3,0	NS	4,0	NS	3,0	NS	2,0
EF	18,0	EF	5,0	EF	2,0	EF	2,0	EF	2,0
LO	3,0	LO	2,0	LO	2,0	LO	2,0	LO	2,0
OU	27,0	OU	7,0	OU	5,0	OU	5,0	OU	5,0
LS	24,0	LS	3,0	LS	7,0	LS	7,0	LS	7,0
PU	4,0	PU	4,0	PU	4,0	PU	4,0	PU	4,0
HU	8,0	HU	8,0	HU	9,0	HU	9,0	HU	9,0
LP	22,0	LP	5,0	LP	9,0	LP	9,0	LP	9,0
QU	31,0	QU	12,0	QU	10,0	QU	10,0	QU	10,0
EH	22,0	EH	7,0	EH	5,0	EH	5,0	EH	5,0
LF	14,0	LF	19,0	LF	25,0	LF	25,0	LF	25,0
LH	6,0	LH	17,0	LH	26,0	LH	26,0	LH	26,0
LM	3,0	LM	8,0	LM	6,0	LM	6,0	LM	6,0
MS	22,0	MS	10,0	MS	4,0	MS	4,0	MS	4,0
RU	9,0	RU	5,0	RU	5,0	RU	5,0	RU	5,0
IU	4,0	IU	8,0	IU	10,0	IU	6,0	IU	6,0
FI	10,0	FI	6,0	FI	16,0	FI	4,0	FI	4,0
HI	5,0	HI	11,0	HI	20,0	HI	8,0	HI	8,0
CP	38,0	CP	21,0	CP	25,0	CP	25,0	CP	25,0
CL	15,0	CL	15,0	CL	15,0	CL	15,0	CL	15,0
DF	5,0	DF	24,0	DF	20,0	DF	20,0	DF	20,0
CS	40,0	CS	19,0	CS	23,0	CS	23,0	CS	23,0
DH	3,0	DH	26,0	DH	17,0	DH	17,0	DH	17,0
EH	22,0	EH	7,0	EH	5,0	EH	5,0	EH	5,0
MP	20,0	MP	12,0	MP	2,0	MP	2,0	MP	2,0

After identifying the pairs that highly affect the total cost portrayed in Table 31 several exchanges were made.

From first iteration to the second “SU”, “FU”, “NS”, “EF”, “LO”, “OU, “LS”, “LP” and “QU” got a major improvement with the expense of “CD” positioning that got worst, even so resulting in a major reduction of the total cost.

The pair “CD” is one with great flow weight, so from the second to the third iteration the focus it. Therefore improving “CD”, but also “DE”, “FU”, “LN”, “EF” and others. From the top “NS”, “OU” and “LS” got worst results, which, in the global run, resulted in reduction.

The fourth iteration analysis focused in the middle to bottom pair connections, but for that to happen a swap was made to the pair departments “LN” and “NS”. Because these stations have the same flow, maintaining the distance proportion of both has no affect in the cost. This move allowed for deeper reduction of the stations “IU”, “FI” and “HI” drastically, resulting in cost reduction.

The final iteration resulted in no reduction of the cost, so for the analysis purpose and given that there will be a future and deeper analysis, the iteration process improving was stopped.

Table 38 - Iterations Total Cost

Iteration	Total Cost
5	657346365
4	657346365
3	670313629
2	727871931
1	1308188800

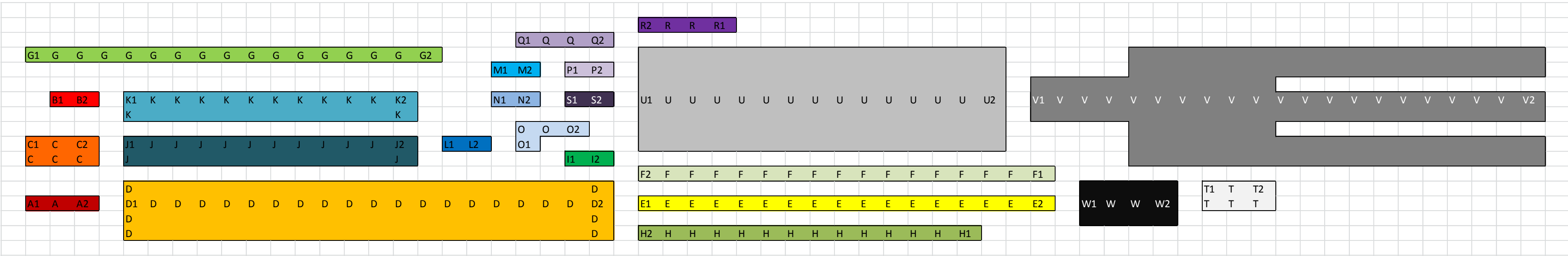


Figure 38 - Layout Iteration 5

Figure 38 shows the final layout iteration in this part of the project.

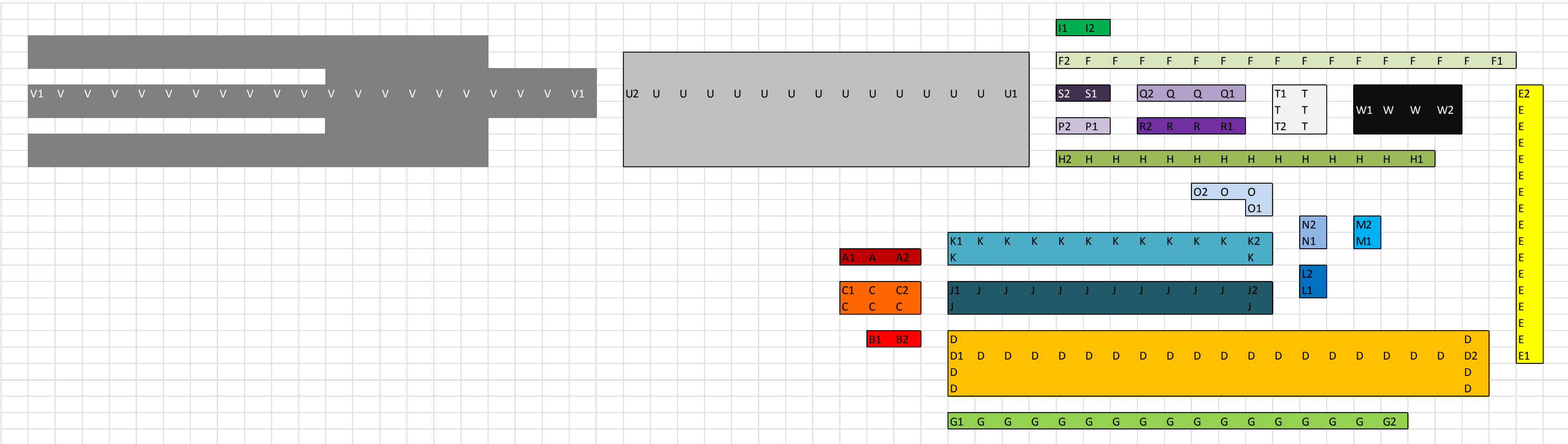


Figure 39 - U Shape Experiment

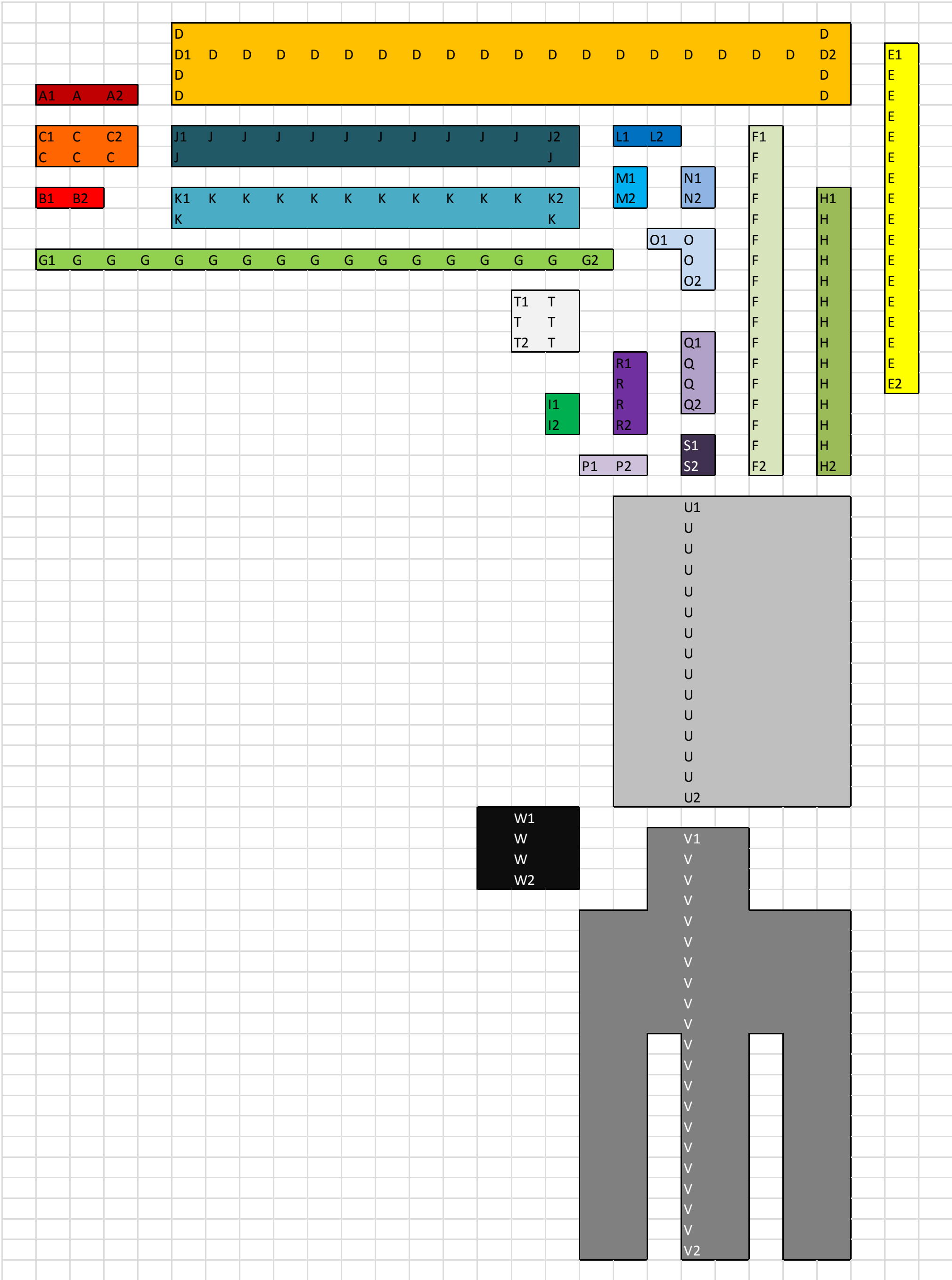


Figure 40 - L Shape Experiment

Typically heuristic methods start from an initial solution, therefor, as previously stated, the first solution as high implication of the future iterations especially on the design/shape. To avoid this drawback, it was created different kinds of initial solutions so that through experience learning some characterization could be taken. Thus Figure 39 and Figure 40, demonstrate a “U” and an “L” shape layout design with interesting results.

Iteration	Total Cost
U Shape	901819777
L Shape	910912250

Figure 41 - Different Shapes Total Cost

Figure 41 determines the total cost of the preceding layouts.

4.1.2 Final Analysis

This topic will initially address the evolution process that was taken to get to the previous results, and then discuss the findings.

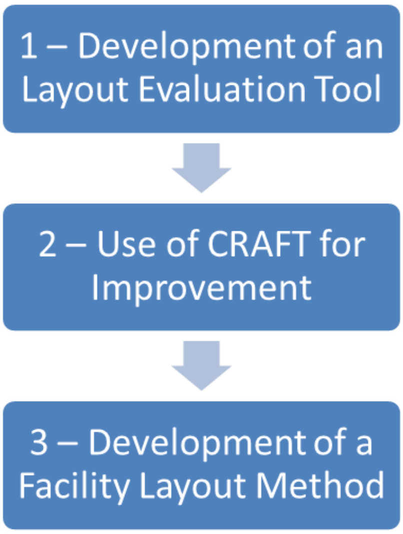


Figure 42 - Layout Determination Process

4.1.2.1 Development of an Layout Evaluation Tool

Firstly it all started with the analysis of the data from the case study, followed by the need to get an optimal facility layout design as a plus for the dissertation project. Therefor with the data provided it were sorted and constructed new tables and graphs to help this objective, like Table 12, Table 13, Figure 14 and Figure 15.

The result was the Table 32 with a 2 dimension map for layout evaluation. This tool used rectilinear distance calculation. The objective is the same, the minimization of the sum of the movement cost plus the amount plus the distance given by equation (8). The approach for the layout construction was a trial and error using the distance reduction of the weightiest interdepartmental flow.

Table 39 - Initial Layout Evaluation Tool

Layout	1	2	3	4	5	6	7	8	9	10
1	A	D	C	J	P	B				
2	H	E	K	L	N	Q	T			
3	I	F	M	O	S	R	G			
4										
5										
6										
7										
8										
9										
10										

Several trails were made and the results were promising and the analysis can be viewed in Table 33.

4.1.2.2 CRAFT method for Layout Improvement

The search for automatic tools that could confirm, calculate or improve the layout lead to the CRAFT method and the Facility Layout add-in developed by Paul A. Jensen [4].

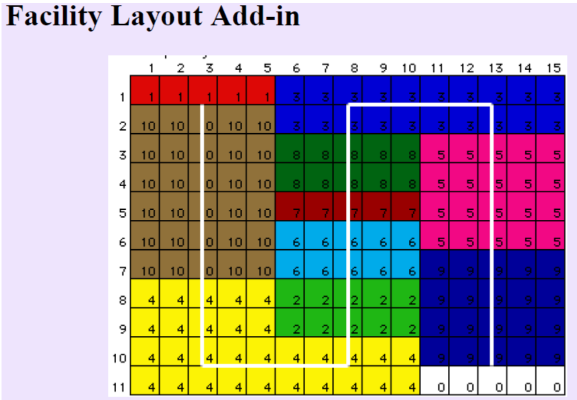


Figure 43 - CRAFT Facility Layout Excel Add-in

The excel add-in tries to find the layout of the departments within the facility that minimizes the total cost of material handling.

It accepts as data: the list of departments, the physical sizes of departments, part flows between departments, material handling costs between departments and the size of a proposed facility.

It is a powerful tool, but given the specifications of the case study layout it was difficult to implement and get the expected results.

The major drawbacks were: difficult to handle a big number of departments with great differences in shapes and proportions, to lock the shapes, to get the flow from specific points of entering and exit and the size limitation of the layout. This lead to interesting results but not approximated to reality. Yet it was a great starting point to raise the awareness of the variables and calculations within a heuristic model like this one.

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4 https://www.me.utexas.edu/~jensen/ORMM/omie/computation/unit/lay_add/lay_create.html

Table 40 - First Evaluation Tool and CRAFT Total Cost Analysis

	Experiment	Layout	Total Cost
CRAFT	14,00	4X5	117931012
	13,00	3X6	118725145
	12,00	4X5	121681212
	11,00	4X5	119186389
	10,00	2X10	130752608
	9,00	10X2	142740636
	8,00	2X10	164523594
Trial and Error	7,00	3X7	118725145
	6,00	4X5	119049330
	5,00	3X7	118725145
	2,00	3X7	197084721
	4,00	2X10	145508776
	3,00	2X10	160813913
	1,00	2X10	222563064

Table 33 presents the results from topic 4.1.2.1 and 4.1.2.2 were it can be examined different layout solutions from the evaluation tool and the CRAFT method. The optimal solution encountered was actually discovered by the both methods, the solution layout of 3 units of length by 7 of width, with a total cost of 118725145.

The CRAFT tool delivered a better solution, the last experiment with total cost of 117931012, but unless the facility layout was in a 3 dimensions design, which in this case it was not considered as a possibility, the placement of the entering department in the middle provoked the disregard of this solution.

4.1.2.3 Development of a New Facility Layout Method

The development of a new facility layout method that could overpass the drawbacks of the methods analysed was taken in consideration given the necessity to approximate the results to the real case scenario.

Therefor several methods were studied as stated in topic 3.2.1, and the closest to the desired objectives was the pairwise method. This method and many similar to it as the objective function to minimize the sum of distances plus material flow plus the movement cost, equation (2). This method uses distance calculation from centroid and typically uses a gluttony method where only 1 pair is analysed. It is very simple if departments are of same size and shapes.

The solution was to develop a method similar that could tackle these limitations. The objective function is similar, equation (8), which uses rectilinear distance calculation from point of exit to entering, allowing also the rotation and inversion of the departments. The final constrain was related to the shapes and sizes, so an operation was developed to relativize the proportions and with the help of an excel 2 dimensions map tackle the shapes, so the method uses a set of rules that with the visual awareness of the departments given to the modeler results in a realistic layout through a set of iterations.

4.2 Buffer Sizing Simulation Analysis

Buffer sizing simulation analysis presents the results gathered from the modelation of the case study. As previous affirmed, to achieve the goal, the buffer calculation, it was used a set of data inputs and AnyLogic function blocks complemented with java functions to get the expected behaviour and a case study yearly product demand for the experimental run purposes.

After several implementations and corrections the final result was validated through a series of tests and trials. The tests made were, for example, printing to the console information relative to the agent's parameters and AnyLogic function blocks expected outputs. The final set of results was validated with a series of repetitive runs/simulations where the outcome was exactly the same.

Table 41 - Maximum Buffer Simulation Results

Buffer Number	Maximum Buffer
buffer1	0
buffer2	0
buffer3	13594
buffer4	1
buffer5	1
buffer6	1
buffer7	0
buffer8	1
buffer9	217
buffer10	1
buffer11	1
buffer12	1
buffer13	1
buffer14	1
buffer15	1
buffer16	1
buffer17	1555
buffer18	777
buffer19	1
buffer20	0
buffer21	2
buffer22	0
buffer23	0

Because of the workstation/laptop lack of resources the simulation was implemented with a factor. This issue will be addressed further in the dissertation, but essentially one major constrain in the simulation was the quantity of agents that flowed in the model. That led to a great increase in simulation time, and often the breakdown of the run/simulation. Therefor a factor was applied to reduce the number of agents, but to maintain an approximation to the real scenario that factor was also applied to the processing time. For example, a factor of 10 results in one tenth of the product volume and a ten times higher processing time, this way keeping a relative approximation to the case study. Because of the same reasons the implementation of setup time was turned off and given that this production model is a pull type with a great amount of materials per batch, it was not considered any type of implementation to deal with it.

Table 34 displays the final result. It can be observed several buffers with 0 or 1 maximum amount. This can be explained because the processing times are similar and/or inferior at the downstream departments.

There are 3 similar cases, buffer 3, 17 and 18 are the buffers of the departments that initiate the all production, because product orders arrive at a specific time of the day and with a great demand of products, that creates a great amount of materials in the beginning of the production floor waiting to initiate the processing.

Buffer 9 is a middle department and because of an higher processing time that the upstream departments creates a bottleneck and consequent need for a big buffer.

Buffer 21 has a maximum buffer of 2 units, even so the processing times are small, because it was not considered setup time and this station aggregates all of the routing sequences, it is a point for potential problems consequent bottleneck and great amount of WIP with results in the need for a buffer or other solutions to accommodate that.

With these results there is a need for allocation of space to allow the materials to wait in the buffers prior to the departments. The results for the maximum buffer of departments 3, 17 and 18, are very high which may lead to a sensation of a big alteration of the layout, but because they are the stations on the beginning of the production line and independent from each other there is no impact to the layout because the buffers can be allocated before and with no major change to the solution design.

That is not the case of department 9 and 21 nevertheless, especially department 9 there is the need to allocate size to that department to mitigate this problem and allow the physical placement of the materials to be processed. The next topic will address it.

The buffers discussed raise a question, what amount of space should be allocated and how can it be calculated accordingly to the materials.

4.2.1 Buffer Physical Space Determination

From the case study data analysed, there is little information regarding the size of the materials and the relation to the department's size so for this calculation several assumptions will be made.

Table 42 - Material Length

idComponent	length	Rework	Pcs/pal	Scrap
1	1,8	0,01	476	0,028
2	1,8	0,01	476	0,028
3	2,1	0,01	1666	0,028
4	2,1	0,01	451	0,028

From Table 35 it can be determined the length of the materials but not the width neither the relation to the size of the departments because they were determined through the relative proportion to each other and not the actual size. Even so the length is present, because there are several length differences between material type it raises the question to what measure should be considered. Thus several assumptions had to be made.

The first assumption is the length, for that it was used the mean value of the length of the materials by type rounded up to the decimal. Secondly the width, it was assumed that because of the representation of the length and not of the width, that should suggest a smaller and not relevant measure, so it was assumed one quarter of the length. Thirdly, how do the measures of the materials and the departments relate. For this purpose the main idea was to relate the material and the machine that processes it, and with that in mind 5% could be a good value. Lastly, the buffer disposition or rack store characteristics are important to discuss how many aisles and levels. Analysing the case study it could be implied that the low processing times and the length of material must have easy access and probably a conveyor.

$$B_{Asize} = \frac{l * w * r * M_{Bi}}{n_{aisles} * n_{levels}} \quad (12)$$

- B_{Asize} – Buffer area size;
- L – Length;
- W – Width;
- M_{Bi} – Maximum buffer of department i;
- N_{ailses} – Number of aisles in the rack store;
- N_{levels} – Number of levels in the rack store.

Table 43 - Buffer Area calculation

Buffer	Average Material Length	Material Width	Departments Relative Proportion	Maximum Buffer Size	Number of Aisles	Number of Levels	Buffer Area
3	1,9	0,475	0,05	13594	4	3	51,1
9	1,9	0,475	0,05	217	1	1	9,8
17	1,9	0,475	0,05	1555	2	3	11,7
18	1,9	0,475	0,05	777	2	3	5,9

Table 36 determines the buffer area of the discussed buffers using equation (12). The calculation of buffer 21 was not considered because the low amount needed would not affect the space of that workstation.

Table 44 - Final Buffer Dimensions

Buffer	Initial Buffer Area	Buffer Length	Buffer Width	Final Buffer Area
3	51,1191	11	5	55
9	9,79213	5	2	10
17	11,6949	4	3	12
18	5,84369	3	2	6
21	0,09025	0	0	0

Table 37 demonstrates the final result of the calculations with the roundup of the values.

Concluding, buffer sizing can be difficult to predict given a complex case study, but with the help of simulation that completely changes. With the possibility to simulate changes in the demand, the layout, seasonally peaks, break downs and many other factors it can be calculated with great accuracy as pointed out by this approach.

During the model implementation process several difficulties were encountered that limited the prosecution of greater conclusions and more functionality.

Feature	Free AnyLogic® PLE¹	AnyLogic® University Researcher²	AnyLogic® Advanced	AnyLogic® Professional
AREAS OF USE				
Education and Self-Education	✓	✓	✓	✓
Public Research in Universities²	-	✓	✓	✓
Commercial Projects and Private Research	-	-	✓	✓
MODEL SIZE				
Unlimited Number of Agent Types in One Model	limited to 10	✓	✓	✓
Unlimited Number of Embedded Agents/Blocks in One Agent	limited to 200	✓	✓	✓
Unlimited Number of System Dynamics Variables in One Agent	limited to 200	✓	✓	✓
Unlimited Number of Dynamically Created Agents	limited to 50,000	✓	✓	✓

Figure 44 - AnyLogic Editions Comparison

The initially constrain encountered was the limitation of the building blocks which stopped the addition of functionalities that could modulate a more realistic behaviour. Secondly the restraint number of agents reduced largely the capability of injecting inputs/agents through the demand in such a disproportion to reality that could have affected the results. Figure 44 presents the comparison of editions were the limitations discussed can be pointed out. To solve these issues it was requested a university edition later on, which was granted by AnyLogic. That was a major advance in the model capabilities.

Afterwards with no limitation on the software side, the problems appeared from the hardware. The simulation of a model in a five year hold, low budget computer, proved to be time consuming, and leaded to a deep analysis and careful function implementation process. That problem was discussed with the AnyLogic supporting team with unfortunately no solution. Some functionalities of the program were then avoided because of the use of "for" cycles and substituted by java code, many functions where simplified, some production methods were avoided and as stated, the buffer simulation was made possible through application of a input factor to reduce the number of agents. One of the conclusions about the model simulation speed was that the number of agents related to the speed, higher number of agents, higher simulation time. Even dough the simulation could be left running, regrettably none of the experimental runs ended because of computer friezing, lagging and breaking out with unexpended errors.

In the end the results, given the difficulties and the barriers overcame, give a great value to the achieved results.

4.3 Facility Layout and Buffer merged Analysis

This topic presents an analysis to the consequences of the buffer determination on the previous layout.

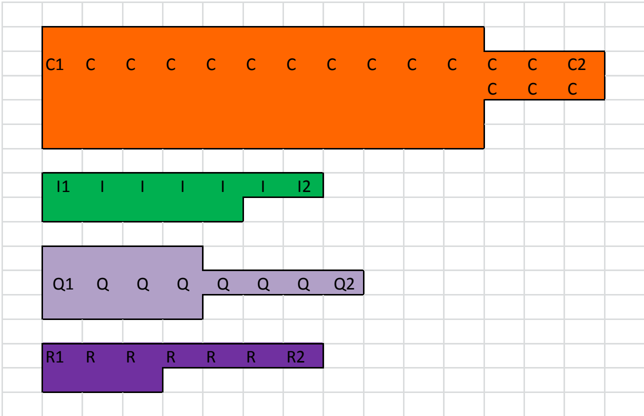

Figure 45 - Department Layout Update

Figure 45 demonstrates the necessary department layout update to accommodate the buffer calculation. Given these changes a new improvement process started using the method described earlier.

Table 45 - Iteration Process Table

Iteration 1	Distance	Iteration 2	Distance	Iteration 3	Distance	Iteration 4	Distance	Iteration 5	Distance	Iteration 6	Distance	Iteration	Distance
CJ	2,0	CJ	2,0	CJ	2,0	CJ	2,0	CJ	2,0	CJ	2,0	CJ	2,0
JL	2,0	JL	2,0	JL	2,0	JL	2,0	JL	2,0	JL	2,0	JL	2,0
SU	2,0	SU	2,0	SU	2,0	SU	2,0	SU	2,0	SU	2,0	SU	2,0
CK	5,0	CK	5,0	CK	5,0	CK	5,0	CK	5,0	CK	5,0	CK	5,0
KL	5,0	KL	5,0	KL	5,0	KL	5,0	KL	5,0	KL	5,0	KL	5,0
CD	6,0	CD	6,0	CD	6,0	CD	6,0	CD	6,0	CD	6,0	CD	6,0
DE	2,0	DE	2,0	DE	2,0	DE	2,0	DE	2,0	DE	2,0	DE	2,0
FU	5,0	FU	5,0	FU	5,0	FU	5,0	FU	5,0	FU	5,0	FU	5,0
LN	3,0	LN	4,0	LN	4,0	LN	4,0	LN	3,0	LN	3,0	LN	3,0
NS	3,0	NS	2,0	NS	2,0	NS	2,0	NS	3,0	NS	3,0	NS	3,0
EF	2,0	EF	2,0	EF	2,0	EF	2,0	EF	2,0	EF	2,0	EF	2,0
LO	2,0	LO	2,0	LO	2,0	LO	2,0	LO	2,0	LO	2,0	LO	2,0
OU	5,0	OU	5,0	OU	5,0	OU	5,0	OU	5,0	OU	5,0	OU	5,0
LS	7,0	LS	7,0	LS	7,0	LS	7,0	LS	7,0	LS	7,0	LS	7,0
PU	8,0	PU	4,0	PU	4,0	PU	4,0	PU	8,0	PU	8,0	PU	4,0
HU	9,0	HU	9,0	HU	9,0	HU	9,0	HU	9,0	HU	9,0	HU	9,0
LP	3,0	LP	9,0	LP	9,0	LP	9,0	LP	3,0	LP	3,0	LP	5,0
QU	6,0	QU	10,0	QU	10,0	QU	6,0	QU	6,0	QU	6,0	QU	6,0
EH	5,0	EH	5,0	EH	5,0	EH	5,0	EH	5,0	EH	5,0	EH	5,0
LF	25,0	LF	25,0	LF	25,0	LF	25,0	LF	25,0	LF	25,0	LF	25,0
LH	26,0	LH	26,0	LH	26,0	LH	26,0	LH	26,0	LH	26,0	LH	26,0
LM	5,0	LM	6,0	LM	5,0	LM	5,0	LM	5,0	LM	5,0	LM	3,0
MS	3,0	MS	4,0	MS	5,0	MS	5,0	MS	3,0	MS	3,0	MS	5,0
RU	6,0	RU	5,0	RU	5,0	RU	6,0	RU	6,0	RU	6,0	RU	6,0
IU	4,0	IU	10,0	IU	8,0	IU	8,0	IU	7,0	IU	7,0	IU	4,0
FI	15,0	FI	21,0	FI	19,0	FI	19,0	FI	18,0	FI	18,0	FI	15,0
HI	19,0	HI	25,0	HI	23,0	HI	23,0	HI	22,0	HI	22,0	HI	19,0
CP	19,0	CP	25,0	CP	25,0	CP	25,0	CP	19,0	CP	19,0	CP	21,0
CL	15,0	CL	15,0	CL	15,0	CL	15,0	CL	15,0	CL	15,0	CL	15,0
DF	20,0	DF	20,0	DF	20,0	DF	20,0	DF	20,0	DF	20,0	DF	20,0
CS	23,0	CS	23,0	CS	23,0	CS	23,0	CS	23,0	CS	23,0	CS	23,0
DH	17,0	DH	17,0	DH	17,0	DH	17,0	DH	17,0	DH	17,0	DH	17,0
EH	5,0	EH	5,0	EH	5,0	EH	5,0	EH	5,0	EH	5,0	EH	5,0
MP	5,0	MP	2,0	MP	7,0	MP	7,0	MP	5,0	MP	5,0	MP	3,0

The first solution was an update of the best solution previously determined with the buffer changes. It was used that solution because it is a good starting point.

The second iteration resulted in the change of place of station “M” and “I” with resulted in a better result. Several interdepartmental distances got closer like “LN”, “NS”, “QU”, “LM”, “MS” and “IU”. On the other side “LP” and “RU” got worst.

The third iteration got “IU”, “FI”, “HI” and “MS” closer and dough “LM” got worst the fact that “MS” and “LM” have the same amount of flow makes that if the accumulated distance of both does not change it do not affect the total cost.

The fourth iteration resulted in an arrangement between “QU” and “RU”, the prior got better to consequence of the later but because the flow weight is higher in “QU” it resulted in a lower total cost.

The fifth iteration resulted in a lower cost by the exchange of place o “P” workstation, then resulting in a closer distance for stations “LN”, “NS”, “PU” and “MS” with a lower sum.

Sixth iteration started with a rotation of department “I” which allowed a placement change that got better results for “IU”, “FI” and “HI”.

The last iteration is an exchange of stations “M” and “P” with lead to the total cost reduction. The affect was on “PU” reduction dough it raised “MS” but because “MS” and “LM” have the same flow the exchange did not provoke an accumulated distance affect. Because there was no apparent exchanges that could lead to further improvement the process stopped.

Table 46 - Total Cost Iteration Calculation

Iteration	Total Cost
7	640859847
6	647316607
5	652179331
4	660256999
3	662541285
2	667083612
1	674365899

Table 39 shows the total cost of the iterations made. It can be observed that the process lead to a continuous reduction of the total cost and dough this layout had the addiction of the buffer space, especially for workstation “I”, the improvement process actually got to better results than the initial improvement process.

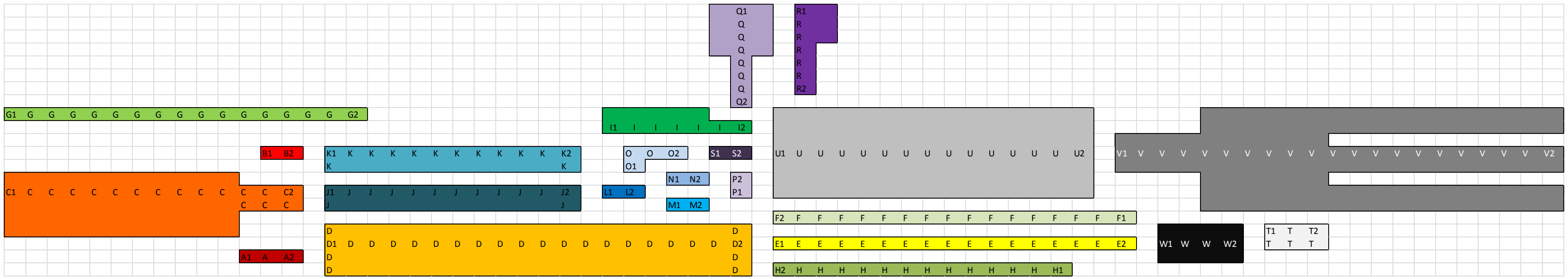

Figure 46 - Final Layout with Buffer Input

Figure 46 demonstrates the final optimal solution for the case study analysed with the addiction of the buffer analysis from the simulation approach. It is important to affirm, as stated by the literature review, that this kind of approaches lead to optimal solutions not the best solution. Nevertheless given the results it can be strongly affirmed that this layout is realistic and reduces the total cost of the material handling which was one of the objectives of the project.

Chapter 5

Conclusions and Further Research

This last chapter presents an overview of all the work done for this dissertation, as well as recommendations and further research.

5.1 Conclusions

Modelling and simulation of production systems have been growing in the global context, following the evolution of computers and the need for the industry to evolve and improve, striving to achieve productive leaps that differentiate them from competition.

The main goal of this dissertation is to analyse and evaluate simulation software through implementation of production system tools aiming to improve the facility layout design. Below it will be address primarily the answers to the research questions.

One of the objectives of this dissertation was the study of the simulation software AnyLogic and its application in the manufacturing systems, thus evaluating the potential and capabilities. It was identified that by supporting the most common simulation methods nowadays, namely System Dynamic, Process-Centric/Discrete Events and Agent based modulation, which can be used simultaneously and combined is a major advantage and delivers great flexibility.

The new Process Modelling Library allows the simple and rapid implementation of manufacturing models because of the building blocks that can easily modulate the behavior of the system and thus easily simulate a great majority of problems.

Whenever the building blocks fall short to approximate the model to reality, the usage of java as an additional programing language solves it. This capability permits the adjustment of the properties of the system and the respective blocks, being one of the most popular programing languages which simplify learning.

Nevertheless, it was observed that even dough the learning curve of AnyLogic and Java is smooth and relative rapid when the modeler wants the implementation of higher complexity models with particular behaviors the programming itself raises complexity also.

Overall the findings and the previous research lead to the previous conclusions but it is also important to state that given the great possibilities and variety of production system tools and methods this objective cannot be fully determined with just one case study implementation and few previous studies.

Even dough there are great advantages for using simulation, there are still constrains and difficulties that hurt the rapid spread of these tools. The simulation model is an approximation of reality and so the assumptions made during implementation should be taken very carefully in order not to produce armful errors that could compromise results. They are as accurate as the input data and very often the gathering of reliable data is difficult. The utility of the outcomes depends on the skill of the modeler and lastly the time and cost of using these tools are important. The implementation of a complex model requires a skilled modeler, probably a team with multifaceted capabilities to aid the process, the gather of accurate data, acquisition of specific software and hardware and usually training lessons for the maintenance of the model. Therefore highly costly and time consuming, but on the other hand the cost of not using simulation should also be taken in consideration, especially the great advantage to have it as a support for decision making diminishing the risk.

Several studies have pointed out the tradeoff, and suggested a set of rules to evaluate when to use it, but that could not be enough because of the rapid change of the markets and respective competition. Therefore an analysis of short and long term benefits and disadvantages should also be made to give further information to the decision.

Several simulation approaches have appeared that address the facility layout problem but still with situations like this case study complexity, more than 50 products composed by more than 250 materials with unique routings through 25 workstations, the models would have been highly complex, time-consuming and should require a high skill on the matter. Nevertheless the heuristics approaches like pair-wise exchange and CRAFT continue to deliver optimal solutions, but regarding the specifics of the problem, the exotic shapes, highly distinct proportions and the particular entry and exit point of the department's layout, even dough they could tackle these needs with additional programing, they are not normally that sophisticated.

Thus the necessity to solve these issues leaded to the development of a similar tool that by using several equations and conceptions of CRAFT solves the problem through an additional set of rules and experiments. The results were promising and highly realistic, granting great confidence in the results and also in the process developed. The steps made are independent of the case study, so this approach can easily be used in other complex layout where the distance is the key problem in the material handling.

But if the facility layout was not calculated trough simulation how can it aid the design. The answer to this question leaded to the study of different methodologies and the buffer sizing was the right candidate because the determination also has a bearing on the performance characteristics such as productivity, flexibility, and specially space utilization for a manufacturing system. In this case would take a major influence in the facility layout design regarding the additional space needed.

Therefor it was built, using the case study, a model that simulates the behaviour of the manufacturing system and determines the maximum buffer size of a typical annual demand using a push type production. There were some drawbacks, as previously discussed, that halted the improving of the simulation, being the lack of computational capacity the major one, which lead to simplifications that prevented further developments that would need more time-consuming functions to emulate other behaviour or production types. Nevertheless the method undertaken has proven to be rigorous and delivers important data, even dough further advances could identify greater improvements and approximate even further the model to the real scenario. The fact that the initial layout design was unknown did not allow a comparison analysis.

Overall the facility layout determination aided by buffer sizing simulation proved to be a major advantage to the final result giving a deeper analysis to the study, a more realistic solution closer to the reality of the production system. Therefore offering arguments that could support with data and conclusions the decision making process for the continuous improvement.

5.2 Further Research

Although the main objectives were fulfilled, several aspects can be exhaustively studied in the future.

The buffer determination could be simulated with the additional setup time and without any reduction factor multiplier permitting a greater approximation to the real scenario.

The simulation of different production strategies pull, with CONWIP and Kanban, and hybrid pull-push could arise more information for production system continuous improvement and buffer sizing determination.

Implementation of the packaging line with a decoupling point between it and production with supermarket sizing calculation could deliver important information to a wider case study analysis.

Incorporation of sifts with brake's and lunch time could give more information and statistics of the working force and workstation utilization.

Modelation of work station break times could also allow better risk management, test stress scenarios and take conclusions to develop mechanisms and methods to eliminate, reduce and predict problems.

Lastly, AnyLogic's functionalities were not completely studied specially the combination of different simulations methods like agent based with discrete event that could allow a deeper analysis.

Appendixes

Table 47 - Work Station Sifts

Resource	Description	Shift name	Break time (hours)
M01R1	Cutting	A	3,25
M02R1	Coating	A	3,25
M03R1	Sawing	A	3,25
M04R1	Wrapping	D	0,25
M05R1	Cross cutting	A	3,25
M06R1	4 side	B	2,75
M07R2	Drilling line	B	2,75
M08R1	2 sides	D	0,25
M09R1	Corner cutting	C	0,75
M10R1	Profile wrapping	D	0,25
M11R1	Wrapping line	D	0,25
M12R1	Cutting machine	A	3,25
M13R1	Edge banding	C	0,75
M14R2	Edge banding	C	0,75
M15R2	Hot dowling	C	0,75
M16R2	Friulmac	C	0,75
M17R2	Frame assembly	A	3,25
M18R2	Auto frame assembly	A	3,25
M19R2	Drilling	C	0,75
M20R1	CNC	A	3,25
M21R1	Buffer	D	0,25
M22R3	Packing	A	3,25
M23R1	Rework	A	3,25
M24R2	Product stacking	A	3,25

Table 48 - Circus Flow Map Data Input

labels A B C D E F G H I J K L M N O P Q R S T U V W X Y
A 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
B 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
C 0 0 0 8641488 0 0 0 0 0 15817669 9736345 306144 0 0 0 325582 0 0 81396 0 0 0 0 0 0
D 0 0 0 0 8488416 153072 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
E 0 0 0 0 0 6553643 0 1934773 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
F 0 0 0 0 0 0 0 0 445034 0 0 0 0 0 0 0 0 0 0 0 7924458 0 0 0 0
G 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
H 0 0 0 0 0 0 0 0 365420 0 0 0 0 0 0 0 0 0 0 0 3042882 0 0 0 0

```
I 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 810454 0 0 0 0
J 0 0 0 0 0 0 0 0 0 0 0 15817669 0 0 0 0 0 0 0 0 0 0 0 0 0
K 0 0 0 0 0 0 0 0 0 0 0 9736345 0 0 0 0 0 0 0 0 0 0 0 0 0
L 0 0 0 0 0 1662777 0 1473529 0 0 0 0 1142143 7007820 6467013 2902798 0 0 5204078 0 0 0 0 0 0
M 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1142143 0 0 0 0 0 0
N 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 7007820 0 0 0 0 0 0
O 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 6467013 0 0 0 0
P 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 3228380 0 0 0 0
Q 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 2427429 0 0 0 0
R 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1126918 0 0 0 0
S 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 13435437 0 0 0 0
T 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
U 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 38462971
V 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
W 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
X 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Y 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

Table 49 - Sankey Flow Chart Data Input

```
C [8641488] D
C [15817669] J
C [9736345] K
C [306144] L
C [325582] P
C [81396] S
D [8488416] E
D [153072] F
E [6553643] F
E [1934773] H
F [445034] I
F [7924458] U
H [365420] I
H [3042882] U
I [810454] U
J [15817669] L
K [9736345] L
L [1662777] F
L [1473529] H
L [1142143] M
L [7007820] N
L [6467013] O
L [2902798] P
L [5204078] S
M [1142143] S
```

N [7007820] S
O [6467013] U
P [3228380] U
Q [2427429] U
R [1126918] U
S [13435437] U

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