BACHELOR THESIS
INDUSTRIAL ENGINEERING & MANAGEMENT

REDESIGNING THE AEROSPACE PRODUCTION FACILITY TO IMPROVE WORKFLOW AND WORKFORCE FLEXIBILITY

J.W. Hegeman
S0174238

FACULTY OF MANAGEMENT AND GOVERNANCE

EXAMINATION COMMITTEE

University supervisors:	**Ir. S.J.A. Löwik**
	Dr. Ir. L.L.M. van der Wegen
Company supervisor:	**Mr. F. Hospers**

FINAL REPORT

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Preface

This report is meant to serve as a thesis paper for the obtainment of a Bachelor's degree in Industrial Engineering and Management, as offered at the University of Twente, the Netherlands. The corresponding research was performed over the course of three months at Aeronamic B.V. of Almelo, the Netherlands. The aim was to design a new layout for the company's Aerospace Production Facility, with which the company could begin preparations for the actual change.

Personally, I like to think that we, i.e. myself and the employees I have cooperated with, have been successful in our aim and have delivered an end product that is satisfactory to all involved parties and will boost the company's performance. Special mention must be given to a number of people for their part in this achievement.

First of all, all operators working at the Repair and Overhaul and Original Equipment Manufacturing departments at Aeronamic deserve praise for their cooperation and proactive participation. Rick Feenstra and Bas Klok in particular have made valuable contributions with their practical ideas in the design brainstorms. I would also like to thank my personal coach Fred Hospers for his aid in the start up phase of the project and for the time spent on checking prior versions of this report. Finally, I would like to thank senior management for their support and the freedom they have given me during the execution of the project. I believe that has significantly enhanced the learning experience.

At the University of Twente, Sandor Löwik deserves my sincere gratitude. During a time where perhaps too many students require a project supervisor due to the upcoming government regulations on study duration, he still found the time to aid me with his advice on the project. This is commendable as well because I had requested a different supervisor at first and had come to regret that decision.

Overall, I am very happy with both the process and the resulting layout design obtained in this project, and I sincerely hope this report reflects some of that enthusiasm.

Jens Hegeman

Summary

The Repair and Overhaul (R&O) and Original Equipment Manufacturing (OEM) departments of the Aerospace Production Facility (APF) at Aeronamic were designated for a layout redesign by senior management. The trigger for the redesign was a planned expansion of the APF. The first objective of the redesign is to improve the flow of work by making it more clear and more visible so that operators can easily observe the performance of production processes. The second objective is to increase the flexibility in assigning operators to stations by making the R&O and OEM workforces work as one team. The APF with the layout before the redesign is depicted in Appendix A on page 55.

Many aspects are to be considered in a layout problem, and so eleven performance criteria were developed with the aid of scientific literature and input from management and the APF's operators. Fourteen constraints also applied to this layout problem, partly because a redesign implies working with an existing building and partly because of certain predetermined wishes from management. The complete set of criteria and constraints can be found in Table 1 on page 17.

A process analysis to find a conceptual layout was performed first, because of substantial liberty in the design process and because of the possibility to almost start afresh, albeit within the limits of the building and some constraints. Both numerical and tacit process data was collected through observation and extensive interviews with operators. Because the R&O and OEM processes differed significantly it was concluded from the analysis that a cell layout with an R&O cell and an OEM cell is the best fit. A product- and functional layout were chosen for the respective cells.

With the cell concept in place, a design method for cell design was chosen once again with the aid of literature. Due to the multi criteria aspect and dual technical-social objectives in the research, a design procedure influenced by the Social Technical Systems approach was chosen. Operators were involved extensively in the design process, with the author acting more as a project leader at times, than as a pure designer. The benefits were that the quality of the layout design improved with the operators' practical suggestions and that their commitment to the solution significantly increased. For the technical aspect of the layout design, the CRAFT algorithm was used to optimise flow of materials.

After several iterations in the design process, six layout alternatives were chosen for scoring on the performance criteria. These scores served as the input for the Analytic Hierarchy Process, which was performed to choose from the alternatives. The AHP and the ensuing sensitivity analysis on this outranking procedure did not yield a definite best solution but left three possible alternatives. The operators were given the final vote in which alternative was to be chosen as the proposed solution to achieve the objectives. This final layout can be found in Figure 23 on page 47.

The changes made to arrive from the layout before the redesign to the proposed layout are in random order: The Repair and Non Destructive Research (NDR) sections are moved from the center of the APF to a new area in the planned expansion. New elements have been added to account for new products (Assembly Scroll Compressor), group equipment that is used by all processes (Common Machine) or improve the flow of work (FO OEM, Fin OEM and Fin R&O). To save space and make the OEM cell's layout a functional layout, the Assembly OEM no longer has dedicated workstations for every product but switches to flexible assembly stations. The final change is that the wall of Inventory Storage Systems (ISS), located in the center of the layout before the redesign, is relocated. All ISS are placed along the edges or walls, with the result that the entire facility is visible from nearly every position and has a much more spacious and open feel.

Implementation of the new layout is to be done in a succession of steps, but phased implementation is not useful. An important factor for the achievement of the objectives is that encouragement and training is required to improve operator skills and abilities for teamwork and continuous improvement. Flexibility and real benefits from 5S will then follow. Social structures like performance measurement and rewards also need to be changed to support the objective of working as a team. Finally, scientific research should focus on finding robust layout design procedures and tools, which are easier to implement and cover a wider range of layout problems, if business is to benefit from their existence.

Table of contents

1 Introduction

This first chapter sets out the research framework for this Bachelor thesis in Industrial Engineering and Management. The framework was developed on the basis of literature on how to develop a research by Verschuren & Doorewaard (2007).

1.1 Project background

This research pertains to a design problem regarding the Aerospace Production Facility (APF) layout at Aircraft subsystem manufacturer Aeronamic B.V. of Almelo, in the Netherlands. Aeronamic produces technologically advanced components in a capital intensive production environment with small series and one piece flow (Aeronamic - Center of Excellence).

The APF houses three main activities; Small Series Manufacturing, Repair and Overhaul (R&O) and Assembly of Original Equipment (OEM). R&O and OEM are the two activities considered in this research. They are currently performed in two separated areas or cells. The two cells are shown in a floor plan in Appendix A. The R&O area is currently organised as a line of workstations, whilst every product in OEM has its own dedicated workstation with practically all tools present at the station. Now, three drivers can be identified for senior management's wishes to redesign the facility.

Yearly demand for R&O of Aeronamic's existing product base of the Load Compressor 350 series is expected to increase from 200 to 300 in the next five years (Vries de, Introduction layout problem, 2012). Two new Compressor products are also expected to enter in OEM production in the near future. Management wishes to meet this demand with existing resources, so an increase in productivity is required.

In general, management wants an improvement in the workflow for all processes in R&O and OEM to achieve this increased productivity. They believe that a clear flow of products through the facility should lead to waste reduction because wasteful activities will then be visible to operators. They have pinpointed a facility layout redesign as one of the opportunities for this improvement. After having successfully redesigned the adjacent Large Series Manufacturing (LSM) facility with Lean manufacturing techniques, the APF is next.

Finally, the R&O and OEM teams have grown to operate as independent teams due to a wall of inventory storage systems separating them. Management wants to increase flexibility in assigning the operators between the departments so they can deploy them where they are needed. They hope a new layout will unite the teams into one and believe that will, in turn, make it easier to deploy people where they are needed, thus increasing operator productivity across all processes. Also, the cluttered layout makes it difficult for supervisors and operators to see the progress of work. This hampers flexibility as well because operators do not know if they can or should assist elsewhere.

1.2 Research objective

The objective of this research is to systematically find a new layout for the R&O and OEM sections in the Aerospace production facility which will both improve flow in the production processes and increase workforce flexibility, by applying methods from theory on plant layout design, employee productivity and flexibility and by analytically appraising the possible solutions.

To clarify the choice for the general objective 'improve flow', as opposed to the more specific and common objective of minimal flow length for high efficiency, one must realise that Aeronamic employs techniques from the Lean manufacturing philosophy profoundly in its processes. An important Lean principle is visibility, which states that "anyone should be able to see how a process is performing at all times" (George, Rowlands, Price, & Maxey, 2005). Management desires this visibility of flow above all else as a starting platform for efficiency gains. For this reason, an optimal flow in this research does not necessarily mean the shortest flow. A formal definition of optimal flow will be given in Section 1.6.

Achievement of this goal will give Aeronamic a founded blueprint for their new layout. It will first and foremost be the input to actually restructure the production hall, but can also serve as a tool to inform employees of the reasons for and possible gains of the layout change.

1.3 Research questions

To achieve the aforementioned objective, the main research question is as follows:

What is the best layout for the R&O and OEM sections in the Aerospace Production Facility to optimise workflow while also increasing workforce flexibility between the two sections?

Good criteria and constraints are perhaps most important to arrive at a satisfactory layout solution. Defining them early saves time and effort by preventing research into layouts that do not fit.

1.1 What are the criteria for a layout solution to achieve the objectives of optimal workflow and flexibility, according to the literature and to Aeronamic's management and process operators?
1.2 How can these criteria be applied to Aeronamic's situation?
1.3 Which constraints apply to the layout design for Aeronamic?

There is an opportunity to start afresh with the layout, so to maximise potential benefits the layout design should start at a conceptual level before progressing into detailed design (Muther, 1973). The first step is therefore to select an appropriate general layout within the constraints.

2.1 Which characteristics of the production process determine the applicability of layouts in theory?
2.2 What are the characteristics of Aeronamic's R&O and OEM processes?
2.3 Which general layouts from the literature are applicable to the R&O and OEM processes?
2.4 Which general layout fits best to the processes performed at R&O and OEM?

Moving from a conceptual layout to a detailed design includes generating alternative solutions (Francis, McGinnis Jr, & White, 1991). In the detailed design phase, many methods may exist to generate alternative layout solutions, so selecting an appropriate method is important.

3.1 Which design methods to generate layout solutions from the remaining concepts exist in the literature?
3.2 What is each method's ability to deliver good solutions according to the literature?
3.3 Which design method applies best to Aeronamic's situation?

The final step towards achieving the goal is judging the solutions with the criteria and constraints and choosing the best solution to obtain a recommended design.

4.1 Which decision making method is best used in Aeronamic's case to evaluate the alternatives with the required criteria?
4.2 What is the best layout solution to solve the main research question for Aeronamic?

1.4 Data collection strategy

Deciding on criteria and constraints for the new layout was twofold. Obviously, literature was consulted for general guidelines but management objectives and tacit knowledge from process owners was very important too. Interviews were used to acquire this information because they offer great depth in information and also allow actively pursuing new information during the interview. Group sessions with process owners to discuss criteria, generate ideas and improve layout solutions were also held, because this is known from Lawrence (1969) to improve the quality of the eventual solution, and has the added benefit of increasing commitment to the change in layout.

For the conceptual step in the design process, information from the literature on facility layout and its determinants was required. Sources of literature for all theoretical research questions were the university library, scientific article databases and the internet. The theory has been applied to

Aeronamic’s situation. Therefore processes had to be defined carefully. Interviews with process owners and physically following the production process provided the necessary insight.

With a desired conceptual situation in place, literature on methods for layout design were reviewed to find a suitable method for Aeronamic’s situation.

The generated alternative solutions had to be judged with the criteria and a multi criteria analysis was required due to the presence of multiple criteria. After choosing a method with the aid of a short review of the literature on this topic, the best layout was selected after scoring to complete the project.

1.5 Expected results

Achievement of the research objective within the desired time frame was challenging but possible. First of all, management support was high, meaning that resources, mainly employees’ time, for this project were available. Considering that interviews with process owners were a primary source of information that was very valuable. The systematic structuring in this research also made monitoring of progress straightforward, with feedback loops with the process owners ensuring practicality. Within these circumstances, a satisfying new layout with new ideas was expected.

1.6 Key terminology

To make explicit what will be treated in this thesis, three key terms are now defined.

The layout of an operation refers to “how the transforming resources are positioned relative to each other and how its various tasks are allocated to these transforming resources” (Slack, Chambers, & Johnston, 2007). The process design, which determines which tasks and transforming resources are required to produce a product, is assumed given and not subject of this research.

Effective flow within a facility is defined as “the progressive movement of goods, materials, energy, information and or people between the departments from origin to destination” (Tompkins, White, Bozer, & Tanchoco, 2003). The key concept in this definition is progressive, so an optimal workflow means that work should only flow towards the destination, and ideally does not experience backtracking and crossing over movements. Clean flows with no backtracking or crisscross movement are also advocated by Lean because backtracking and crossovers are non-value-added or waste. Furthermore, buffers of Work in Process (WIP) within the flow are also regarded as waste. Therefore these are to be minimised as well according to George, Rowlands, Price, & Maxey (2005).

Workforce flexibility refers to “an organization's ability to adapt its human resources in a manner appropriate to increasingly changing environmental conditions. This means that firms can quickly and effectively meet human resource staffing needs with qualified and capable workers and that workers have multiple skills, with the ability to learn more as new demands require” (Keiser & Ferris, 2012).

1.7 Report overview

Figure 1 on the next page graphically depicts the research framework for the entire project. The information in bold lettering in the black boxes is the information that will be used to answer research questions. The source of that information, e.g. scientific literature or the company’s employees, is shown in normal lettering underneath the bold lettering. The employees mentioned can be management, operators or both. The red boxes contain the resulting outputs from a discussion or analysis and are thus answers to research questions. These outputs also serve as inputs for the following step(s). The reader may have noticed that most information shown in this figure has not been discussed yet up to now. That information is discussed in the following chapters and this framework will serve as a guide through the chapters as the report progresses.

In short, the research questions 1.1 till 1.3 about criteria and constraints are dealt with in Chapter two. Chapter three ensues with research questions 2.1 till 2.4 to select a conceptual layout. Research questions 3.1 till 3.3 and question 4.1 are then answered in Chapter four to obtain the design- and decision making process, thereby completing the project’s theoretical framework. The answer to the final research question 4.2, which is the best layout solution for Aeronamic, is given in Chapter seven. This is because chapters five and six first present the activities performed in the design of layout alternatives and during the decision making process.

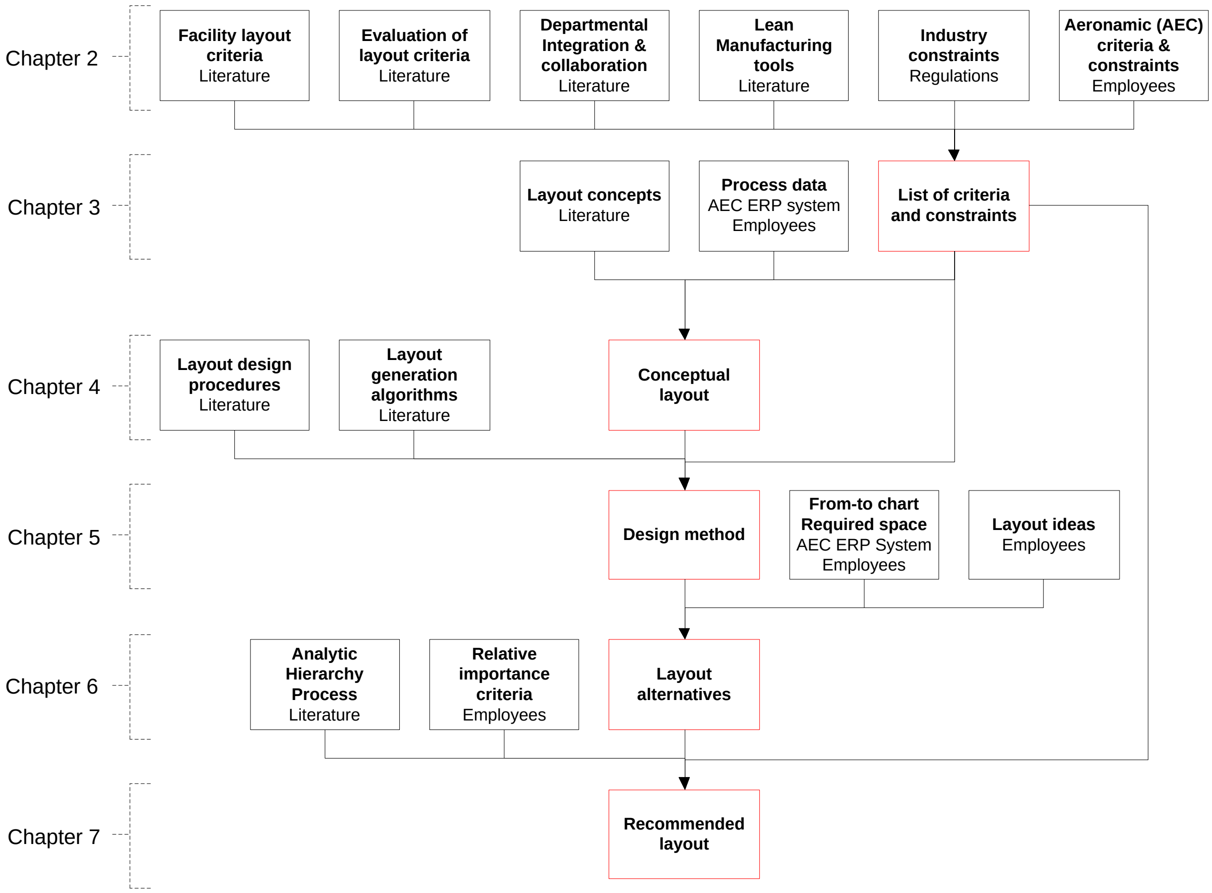


Figure 1: Research framework with overview of chapters

2 Criteria and constraints

This chapter concerns the first three research questions from Section 1.3. First, criteria are formulated from the research objectives flow and workforce flexibility and from the desired Lean principles. These are discussed more extensively because they originate directly from the objectives of the redesign. Along with other criteria from the literature, they are then operationalised for application at Aeronamic. Constraints are determined last. The result is an operationalised set of criteria and constraints for the layout solution, which can be used for evaluation and as guidance during the generation of alternative layout solutions. At the end of this chapter, Table 1 gives an overview of all criteria and constraints.

2.1 Criteria from research objective and Lean philosophy

Flow

According to Slack, Chambers & Johnston (2007) the flow objective can be split into two components, length of flow and clarity of flow. Length of flow is ideally short, which implies minimizing the distance travelled by materials. For clarity of flow recall the definition in Section 1.6. An effective and thus clear flow is progressive from origin to destination, so backtracking and crossing over is undesirable. The following two performance criteria result:

1. Minimal length of flow
2. Minimal backtracking and crossovers of flow

Workforce flexibility

Wright and Snell (1998) found that workforce flexibility is almost exclusively treated from an HRM perspective in the literature, with authors identifying the employee as the defining factor. The focus is on employee skills through the qualitative aspect of training, because a greater skill set results in greater flexibility. An empirical study by Upton (1995) on operational flexibility concluded that employees were indeed and by far more important than any technical factor in determining flexibility. Training and skills are outside of this research's scope though, as it is not impacted by layout design.

A less advocated factor in determining flexibility is employee behaviour. “Employees who possess a variety of behavioural scripts and are encouraged to apply them in appropriate situations rather than follow standard operating procedures increase the likelihood of the firm identifying new competitive situations and responding appropriately” (Wright & Snell, 1998). Employee behaviour, unlike skills, might be subject to indirect influences from factory layout, but no research is available on this topic.

Looking beyond the HRM perspective on workforce flexibility, literature on teams and integration of business processes provide a better foothold for more flexibility in assigning operators. Integration is defined as “a process of interaction and collaboration in which departments work together in a cooperative manner to arrive at mutually acceptable outcomes for their organization” (Pagell, 2004). As this is what management wants operators at R&O and OEM to do, although they defined it differently, interaction and collaboration is desired and will thus be explored further.

Pagell (2004) found from empirical research that several key drivers exist for the level of integration.

- Structure: working in cross functional teams, high job rotation and a facility layout with little boundaries separating departments boost integration
- Culture: cultures boasting open communication and joint problem solving increase integration
- Communication: Information technology systems and formal meetings help, but “informal communication that occurs in real time as problems and opportunities present themselves, is a key to team performance” (Pagell, 2004). Results also showed that physical proximity is a key driver for informal communication
- Measurement and rewards: rewarding employees along common goals boosts integration
- Consensus: people must know they are pursuing the same goals if they are to work together
- Top management support: management must encourage interaction and collaboration

Mintzberg, Dougherty, Jorgenson, & Westley (1996) conducted a research on how collaboration works in general, not distinguishing between intra-organizational- or inter-organizational collaboration. They argued that collaboration amongst actors works along nine core principles, the most relevant for this research being that people should be enabled to work face to face on issues and that formal techniques for collaboration like meetings are never as effective.

To complete the discussion on workforce flexibility, two meetings with employees to discuss criteria were held. The meeting with senior management clarified the objective without yielding new criteria, but the meeting with the R&O and OEM workforce gave practical insights. The operators expressed their desire to work more as one team. The key factors to enable this in their opinion are being informed about priorities, having an overview of all Work in Process (WIP) in the APF and being able to communicate better (Operators, 2012).

Summarizing, drivers for integration affected by the layout are the amount of physical boundaries separating the departments, the physical proximity of departments requiring informal communication and the visibility of WIP for operators. This results in the following criteria having been identified for integration of the R&O and OEM workforces and thus workforce flexibility.

3. Minimal separation of departments by physical boundaries
4. High proximity of departments requiring informal communication
5. High visibility of WIP

Lean

The following discussion on Lean tools is largely based on George, Rowlands, Price, & Maxey (2005). The purpose of Lean tools is to ensure the process can meet customer demand and that lead time and cost are reduced. This is achieved by eliminating non-value-added activities and waste from the process. Apart from visibility of flow and minimal WIP in the process as discussed earlier, other elements of Lean that Aeronamic has embraced are 5S and Visual Process Controls.

5S is a basic method for organizing a clean, safe and high performing workplace. Key for 5S is that everyone is able to distinguish between normal and abnormal conditions at a glance. It is seen as the foundation for continuous improvement, zero defects, cost reduction and a safe work area, because operators will be able to see whether all the required resources are available to them. 5S involves five S'es or steps. These are in order: Sorting needed items from those that are not needed, Setting in order the items so they can be retrieved easily when needed, Sweeping the workplace to keep it clean, Standardizing the first three S'es and Sustaining the established procedures.

Visual Process Controls are the preferred Lean tool to maintain the use of Lean processes. Examples are information boards which visually inform operators about performance, the WIP and priorities. They also indicate the standardised way of working.

A key social concept of Lean is employee involvement. The operators must be empowered and encouraged to continually think about and implement improvements to their workplace to achieve higher efficiency, better quality and meet customer demands better.

To conclude, the layout is to be designed according to 5S principles as much as possible, and Visual Process Controls are the preferred method of communication of process data. Including 5S elements and Visual Process Controls in the layout design concepts means going into extensive detail. During this design process, the focus is on placement of elements rather than detailed design. For this reason, treating them as requirements for each design to have makes more sense. Table 1 therefore also has a design requirements column. Those will be accounted for during detailing of the chosen layout. Last, the benefits of employee involvement in the layout design process are confirmed by Lean, but continued involvement is also important afterwards.

2.2 From theoretical criteria to operationalised criteria for Aeronamic

Additional theoretical criteria

The discussion of criteria from the research objective and Lean in the previous section shows that multiple criteria are to be considered. Indeed, Kumara, Kashyap, & Moodie (1987) already pointed out that layout design problems are usually "ill structured problems" in which both qualitative and quantitative criteria must be considered. Only considering one objective value is simply insufficient to cover the scope of a layout problem.

In the extensive literature on layout design, many performance criteria for layouts have been identified. The following list contains six new criteria, numbers six to eleven, that were not yet discussed and was drawn up with the aid of literature by leading authors on layout design as perceived by their peers. Those authors are Muther (1973), Francis, McGinnis Jr. & White (1991) and Tompkins, White, Bozer & Tanchoco (2003).

1. Minimal length of flow
2. Minimal backtracking and crossovers of flow
3. Minimal separation of departments by physical boundaries
4. High proximity of departments requiring informal communication
5. High visibility of WIP
6. Ease of future expansion
7. High flexibility of layout (for changes in process design)
8. Low required investment
9. Effective movement of personnel
10. High employee comfort (lighting, ventilation, noise)
11. Ability to meet demand requirements

Other criteria not included in the analysis

Three other criteria which are commonly found in the literature are accessibility of workstations, high space utilization and effective supervision. They are left out in this research's further analysis because they are either irrelevant or covered by other criteria, but are mentioned here to be complete.

For Aeronamic, accessing workstations is only important for personnel and inventory replenishment, because very little machines are used in the R&O and OEM processes. The effective movement of personnel criterion already measures accessibility for personnel so it can be left out.

High space utilization is very important if the building is yet to be built, because minimizing used space will generally lower land and construction costs. In this case, the building is already in place and its dimensions are fixed so the criterion is not very useful.

According to Aeronamic's management effective supervision is achieved by visibility of flow and seeing at a glance how the system is performing. Employees also indicated they want the WIP to be visible in the flow. This is already covered by the WIP visibility criterion. Having a facility that can be overseen from every part of the facility, also accounts for effective supervision. The reader will see that this is already measured with other criteria, so a specific criterion for effective supervision is not required.

Operationalization of criteria

The eleven criteria are operationalised for Aeronamic's situation in the following discussion. The reader is reminded that the complete overview of theoretical criteria, operationalised criteria and requirements is given in Table 1 at the end of the chapter.

1. Minimal length of flow

The length of flow is measured by the total weighted distance travelled in meters by the materials in process. A flow represents one product moving from one location in the facility to another. In case of batch movement, the batch of products being moved is counted as one flow. Weights are assigned to the flows by the designer to resemble the "cost" of moving that particular product or batch. Products which are more expensive, difficult or time consuming to move, count more heavily this way. The distance between the locations that have flow relationships is measured and the sum of all these weighted flows then gives the total length of flow in meters.

2. Minimal backtracking and crossovers of flow

Minimal backtracking and crossovers of flow can be achieved by "minimizing the sum of the weighted travel distance in a contrary direction than the general flow of materials" (Drira, Pierreval, & Hajri-Gebouj, 2007). This criterion balances between being quantitative and qualitative, because the user must judge what is a contrary direction. Calculating the distance is done similarly to the procedure above, but obviously only the flows in a contrary direction are counted.

3. Minimal separation of departments by physical boundaries

Separation by physical boundaries is influenced by the amount of fixed elements in the facility. Fixed elements can be walls, columns or in Aeronamic's case, Inventory Storage Systems (ISS). If these elements are placed in between departments that require informal communication, that communication is disrupted. Freedom from fixed elements in between departments means that there are no fixed elements in between departments, so that will be used as the criterion. It is best judged qualitatively by the user, because it will be very straightforward to do so. A quantitative criterion to measure this, developed by Lin & Sharp (1999), does exist, but requires excessive computation.

4. High proximity of departments requiring informal communication

High proximity between departments is a qualitative criterion. It is however, possible to operationalise it to be evaluated quantitatively. Muther (1973) developed the Relationship (REL) chart to maximise the desired adjacency between departments, with adjacency meaning that two departments are located adjacently to each other. A REL chart gives the desirability of adjacently locating a pair of departments by assigning letters (A = Absolute importance, E = Essential importance, I = Important, O = Ordinary importance, U = Unimportant and X = negative importance). An example can be found in Figure 2. After assigning a numerical value to these desirability ratings, the sum of achieved desirability of adjacency is the criterion to be used.

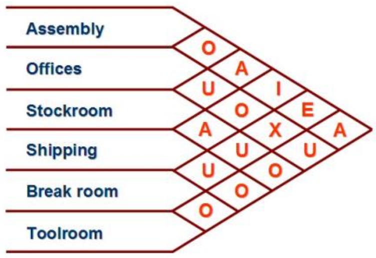


Figure 2: REL chart example

5. High visibility of WIP

High visibility of Work In Process for operators means they know at what stage WIP is when they want to know. This can be achieved through the aforementioned Visual Process Controls. One way is to have one corresponding physical location, for every stage of the process WIP can be in. Specific waiting areas and unique stations for the different activities e.g., can achieve this. Another solution is to have a big board informing all operators about the jobs in the APF. Mainly because a physical flow of products is easier to see and understand than an abstract representation, the former method is used as a criterion. The more WIP stages are physically visible in the APF, the easier it will be for operators to have a good overview. Therefore, the ratio of WIP stages that is physically visible will act as the performance criterion. To illustrate, imagine a process with four stages WIP can be in (in cleaning, in assembly, waiting for inspection and ready for shipment), that has three locations, cleaning, assembly and inspection. The last two stages correspond to the location inspection, but one cannot know without asking if a product is waiting for inspection or already ready for shipment. Then, only two out of four stages are physically visible and this process scores 0.50 on this criterion.

6. Ease of future expansion

Ease of future expansion is mostly affected by the amount of free space in a layout. Maximizing free space thus seems good for this criterion. However, having lots of free space in one corner of the facility will not be very useful if expansion is required at the opposite end and everything still has to be moved. Now, expansion does not only mean reserving space to add an entire production line, increasing the capacity of single workstations is also possible. The concept of scalability, shown graphically in Figure 3, is useful here. Scalability is the ability of a system or process to perform a growing amount of work or be

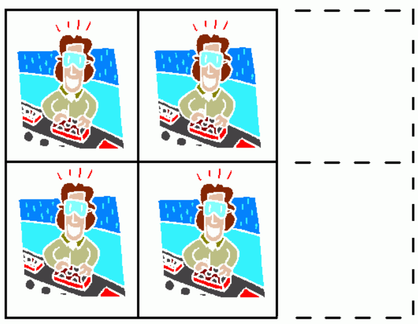


Figure 3: Example of scalability

enlarged to accommodate that growth. The existing four squares with workstations have two empty squares next to them, reserved for possible expansion. For Aeronamic, the total reserved space in m^2 for scalability at workstations will be used as the criterion to judge ease of future expansion.

7. High flexibility of layout

The flexibility of a layout pertains to the ability to change it around for new or changed processes. Lin & Sharp (1999) concluded that to be able to do this effectively, the extent to which a layout is free from fixed elements like partitions, columns and stairs is important. It is slightly different from the freedom from fixed elements criterion used for minimal separation of departments by physical boundaries. Fixed elements may not inhibit communication, because they are not in between departments. However, they can still inhibit flexibility of the layout, because when rearranging the layout one has to place elements around the fixed elements. This subtle difference gives an extra qualitative dimension to these criteria, which is to be judged by the user.

8. Low required investment

The required investment in absolute numbers is not important if it is within acceptable levels for management. However, to determine if a layout is within acceptable levels, the cost of each alternative must be computed. The alternative with the lowest cost is obviously preferred.

9. Effective movement of personnel

Effective movement of personnel can be achieved with sufficient aisle space to move. That is determined by the total aisle length, the department shape ratios and the number of aisle intersections. The department shape ratio is defined as the $\frac{shortest\ side}{longest\ side}$ of the smallest rectangle covering the area of a department. Squares are best for personnel movement so ratios close to one are optimal. Lin & Sharp (1999) also showed that there generally is an inverse relationship between optimal department shape ratios, and aisle length and number of intersections. Therefore, only the former, in the form of the average ratio shall be used to measure effective movement of personnel.

10. High employee comfort

The group session with operators revealed room to work, lighting and noise as the main concerns regarding employee comfort. Employees want sufficient room to work at all workstations, and need good lighting to see what they are doing. Specifically for R&O's Visual Inspection activities, daylight is preferred to artificial lighting. Distance from noisy activities in the Repair section is also desirable. Concluding, freedom from repair noise is a qualitative performance criterion, whilst good lighting at the workstations is treated as a design requirement.

11. Ability to meet demand requirements

The ability to meet demand requirements is the final criterion, which entails that there should be enough capacity to meet the demand for all products. E.g. operators claimed that space for at least two R&O jobs at each process step in the R&O department is required. Regarding OEM, the operators stated sufficient assembly space for all products is required and with the new Scroll Compressor and LC 400 Series on the way, space will also be required for these products once they enter production. Also, management expects that testing capacity for Load Compressors is insufficient to cope with the expected demands. Therefore, space for an extra test cell must be reserved as well (Kleisen, 2012). During the design process, space requirements per activity will be determined. How well these space requirements are met, determine whether the capacity is sufficient. The criterion is thus the ratio of space requirements for workstations fulfilled, with a ratio of one as the goal.

2.3 Constraints

The layout problem in a practical situation is bound to many constraints. For the situation at Aeronamic, numerous constraints exist, all of which have been identified through interviews with employees (Kleisen, 2012) and (Operators, 2012). The list has also been checked for completeness by comparing the constraints with those found in literature by Francis, McGinnis Jr. & White (1991).

1. Safety
2. Repair section must be separated from the other ‘clean’ processes
3. Balancing bench not in Repair section
4. R&O and OEM parts, products and workstations must be ‘separate'
5. Same location for Test cells
6. Same location for Cleaning
7. Same location for Expedition
8. Space in between current Test cells reserved for new Test cell
9. Leave aisle space to enter Large Series Manufacturing area through door
10. Leave room for pallet cart in front of each ISS
11. Only small variations in production equipment allowed
12. Current building dimensions
13. Offices and NDR in expansion, preferably not production
14. Offices in expansion must not be directly accessible from production hall

First of all, safety is considered to be the most important constraint. Getaway routes for people in case of an emergency e.g. are deemed quintessential elements for a satisfactory layout design.

The aerospace industry is subject to strict regulations in their production environment, due to reliability requirements. One example is that “specialised work areas must be placed separate from other areas, to ensure that pollution of that work environment is prevented” (EASA, 2011). Applied to Aeronamic, this means that the Repair section must be kept separate to prevent residuals like sheared metal from polluting the other processes, a phenomenon known as Foreign Object Damage. For the same reason, the balancing bench cannot be in the Repair section. Finally, R&O and OEM parts and products must be prevented from mixing whilst in process. Visually separating them is sufficient in most cases, but used spare parts e.g. may never end up in assembly areas for new products.

Due to prohibitively high investment costs for relocating certain activities, constraints five, six and seven dictate that these three activities remain in the same location and cannot be moved. In between the current test cells, there is free space. Management has already designated that area to be the location for the new Load Compressor Test cell, which was mentioned in the previous section, so keeping that space free is a constraint.

Pallets are occasionally moved from the adjacent Large Series Manufacturing Facility to Expedition. Aisle space equal to the door width is therefore required along the front of the production hall.

Furthermore, logistics employees also require room for pallet carts in front of the Inventory Storage Systems (ISS). Only when that is the case, can inventory be replenished easily so that is also a design constraint.

The existing processes are generally required to use the same tooling and equipment, but minor variations are allowed.

Building dimensions are also fixed because it cannot be altered except for the expansion. The expansion however, is already planned and the additional space has mostly been allocated to office area and Non Destructive Research (NDR). A final constraint is that the production hall must not be accessible from the new office area.

2.4 Conclusion Chapter two: overview of criteria and constraints

In this chapter, research question 1.1 was answered using theory on facility layout criteria and departmental teamwork and collaboration. Lean Manufacturing tools were also discussed for this purpose. Operationalisation with the aid of theory on evaluation of layout criteria, then saw the criteria applied to Aeronamic’s situation, as was required from question 1.2. Finally, to answer research question 1.3, constraints were formulated from input by Aeronamic’s management and after consulting aerospace regulations. The progress within the research framework is shown in Figure 4 on the next page. The complete list of criteria and constraints is summarised in Table 1 beneath the figure.

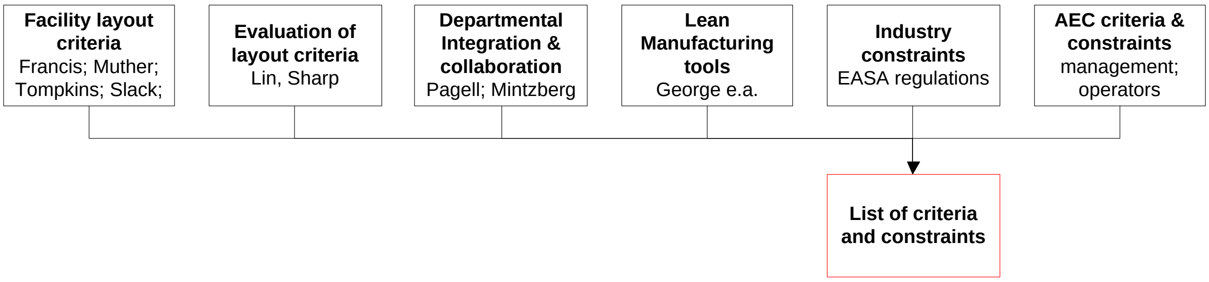


Figure 4: Progress in research framework after Chapter two

Theoretical Criteria	Operationalised Criteria
1. Minimal length of flow	1. Sum total weighted distance travelled (m)
2. Minimal backtracking & crossovers of flow	2. Sum weighted travel distance in contrary directions (m)
3. Minimal separation of departments by physical boundaries	3. Separation by physical boundaries (qual.)
4. High proximity of departments requiring informal communication	4. Sum of achieved desirability of adjacency (qual.)
5. High visibility of WIP	5. Ratio of WIP stages physically visible
6. Ease of future expansion	6. Total space for workstation scalability (m^2)
7. High flexibility of layout	7. Fixed elements in facility (qual.)
8. Low required investment	8. Cost of alternative solutions (€)
9. Effective movement of personnel	9. Average ratio shortest side / longest side of workstations
10. High employee comfort (lighting, noise, ventilation)	10. Freedom from noise by Repair section (qual.)
11. Ability to meet demand requirements	11. Ratio of space requirements for workstations fulfilled

Design requirements	Constraints
1. Layout designed along 5S principles	1. Safety
2. Visual Process Controls used to communicate process and performance data	2. Repair section must be separated from the other ‘clean’ processes
3. Lighting present at all workstations	3. Balancing bench not in Repair section
	4. R&O and OEM parts, products and workstations must be ‘separate'
	5. Same location for Test cells
	6. Same location for Cleaning
	7. Same location for Expedition
	8. Space in between current Test cells reserved for new Test cell
	9. Leave aisle space to enter Large Series Manufacturing area through door
	10. Leave room for pallet cart in front of each ISS
	11. Only small variations in production equipment allowed
	12. Current building dimensions
	13. Offices and NDR in expansion, preferably not production
	14. Offices in expansion must not be directly accessible from production hall

Table 1: Criteria and Constraints

3 Conceptual Layout

Choosing an appropriate conceptual layout is to be performed before detailed layout design can commence. Research questions 2.1 till 2.4 are explored to this purpose. This chapter first presents characteristics influencing conceptual layout, followed by their application to Aeronamic's processes. The possible layouts are presented after which the choice for the best concept is discussed. The selected concept is the input for the detailed design in Chapter five.

3.1 Characteristics influencing conceptual layout

The applicability of conceptual layouts and their corresponding design problems depends on several characteristics of the manufacturing process, which are outlined in the most recent literature survey on facility layout problems by Drira, Pierreval, & Hajri-Gebouj (2007). They are known to be "the production variety and volume, the chosen material handling system, the different possible flows allowed for parts, the number of floors on which the machines can be assigned, the facility shapes and the pick-up and drop-off locations".

Volume – Variety dimension

The most well known factors are the product variety and production volume dimensions. They govern for a large part which of four known conceptual organizations fits best. These organizations are the fixed position-, the functional or process-, the group- or cellular- and the product layout. The relation between volume-variety and the layout organisations is shown in Figure 5.

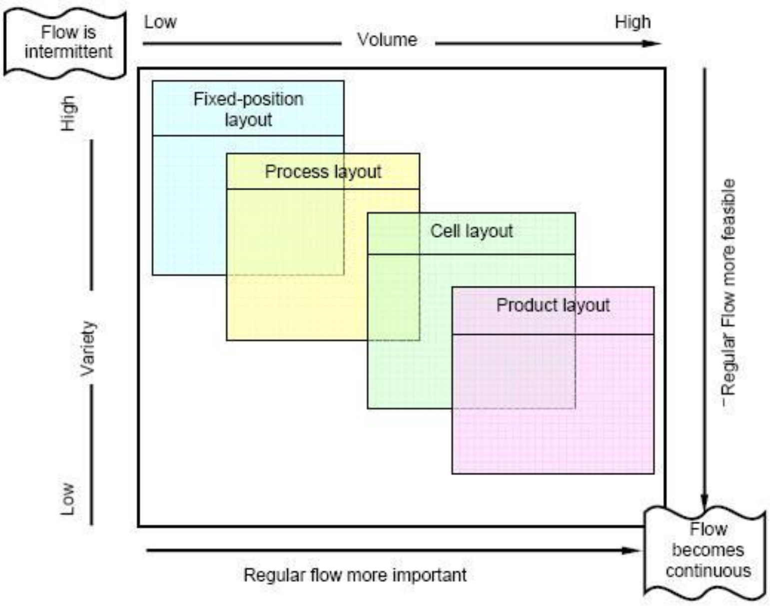


Figure 5: Volume - Variety dimension matrix
Source: (Slack, Chambers, & Johnston, 2007)

Volume pertains to the amount of products that are produced. According to Francis, McGinnis Jr. & White (1991), one must take the expected/desired volumes for the new layout. However, not just the absolute numbers but also the volume in relation to total volume of production matters. For this to be comparable among products, a common measure is required. Operators are the only truly common resource, which makes operator time suitable. $\frac{production\ volume * cycle\ time\ of\ product}{production\ time\ of\ one\ FTE}$ is thus the measure to judge if volume can be considered high or low. Ratios larger than one mean that more than one operator is required, indicating volume is high. A ratio below one is chosen to indicate volume is low, because even one operator has time left to work on other products.

Variety of products concerns the similarity or difference between products that are produced. Measuring variety is difficult. Simply counting the amount of product numbers will not suffice because these products may still be very similar in their production process. It is the difference in the required processes that is interesting. The most time efficient way is to simply ask the operators about the variety in products they produce. Determining all the required process steps is less biased but also much more time consuming. A cross check on required parts per product is performed to be certain.

Material Handling system
A chosen material handling system to move materials, being the use of conveyors, Automated Guided Vehicles, robots, or any other system, also determines conceptual layouts. It is a qualitative factor that determines which type of flow layout is possible due to restrictions in the movements of the material handling equipment. The four types of flow layouts will be illustrated in Section 3.3.

Allowed flows for parts
This factor corresponds to the necessity of backtracking and bypassing in the production process. This is an important factor as it was shown in Section 2.1 to codetermine length and clarity of flow.

Number of floors
This characteristic is straightforward because the more floors available, the more layouts are possible to direct the flow of materials and personnel through these floors.

Facility Shapes
Facility shapes and dimensions can be fixed or unfixed, leaving varying degrees of freedom in the layout choices. When there are angles in the facility e.g., this also influences which concepts to use.

Pick-up and drop-off locations
It is necessary to determine the point where parts enter and leave a facility / department or floor, called the pick-up and drop-off location problem. Where one is able to locate these P/D points also influences which flow layout types are possible.

3.2 Aeronamic's Process Characteristics

The Aerospace Production Facility's redesign corresponds to the R&O and OEM sections. These have different processes, and will thus be treated separately in the forthcoming analysis when necessary.

The R&O section repairs Load Compressors on an on demand basis. All of the LC's follow the same route of processing steps, which are in order of sequence: Disassembly, Cleaning, Non Destructive Research, Visual inspection, Financial reporting, Repair, Assembly, Testing and Final Out preparation. With the exception of cleaning, which is automated, all operations are performed by operators. The processes are depicted visually in the Repair and Overhaul process flow chart in Appendix B.

OEM currently produces six end products, with a further two to be added soon. Ten subassemblies, which are either shipped as spares to customers or used for end products, are also performed. Single spare parts are also picked and shipped. Operators perform the assembly processes manually at an assembly station, as it is a skilled and diverse job. Most products also require operations on varying pieces of equipment which are located elsewhere in the facility, e.g. the balancing bench or measurement table (Klok, 2012). After assembly, a product goes though Testing and Final Out preparation before shipment. An overview of the products and the general assembly process can be found in the OEM process flow chart in Appendix C. Dedicated process flow charts for each product were created, but because they are similar a generalised version is presented here.

Variety
For R&O, the operations performed at a process step are similar every time, except at the Disassembly and Repair steps. At Disassembly, 5% of incoming LC's are disassembled partially and 95% completely. This does not affect the process other than that it takes less time in case of partial disassembly. At Repair, the operations for each LC are unique because all damage and therefore repair actions are different with various tools being used (Feenstra, 2012). This Repair step thus shows high variety in the processes performed, whereas all other R&O steps are similar every time they are performed. R&O in general is thus of low variety, with the exception of Repair, which is high.

From interviews with OEM operators, it can be concluded that the products in OEM are unique in their required parts, tools and operations, except for the LC 350 and LC 400 which are somewhat similar.

To illustrate, when comparing the part lists for the two Starters, and for the two Air Flow Valves, only four out of 86 parts and 16 out of 99 parts were common respectively. For other products, which are not related, all parts were unique (ISAH, ERP Parts lists, 2012). Variety at the entire OEM is thus high.

Volume
Yearly volume for R&O is expected to rise from the current 200 to 300. Because demand is expected to remain stable for the coming years in OEM, historic information from the ERP system can be used. Monthly demand is used because that aggregates demand without ignoring variability. Variability in demand is an issue for R&O because demand is erratic, but not at OEM because demand is known six months to a year in advance (ISAH, ERP Production Orders, 2012). The data is shown in Table 2.

Product	Exp. monthly demand	Cycle Time per product	Ratio Operator	Volume dimension	Ratio Workbench
	R&O				
LC 350	25	44.4	8.34	High	-
	OEM				
ACM	3	15.6	0.35	Low	0.27
BR 700 AFV	16	5.1	0.61	Low	0.47
BR 700 S	22	4.4	0.73	Low	0.56
LC 350	7	15.6	0.82	Low	0.64
Tay 2000 AFV	6	3.7	0.17	Low	0.13
Tay 2000 S	6	5.2	0.23	Low	0.18
	Subs OEM				
Subassemblies LC 350	-	-	0.29	Low	0.22
Subassemblies other	-	-	0.21	Low	0.16
Sum of current OEM	-	-	3.41	-	2.63
	New OEM				
LC 400	2	14.5	0.22	Low	0.17
Scroll Compressor	25	?	-	-	-

Source: (Vries de, Introduction layout problem, 2012) and (ISAH, ERP Production Orders, 2012)

Table 2: Volume dimension for Aeronamic

For R&O, mean demand was 16 per month since 2006, with a standard deviation of 3.7. This is not a shocking variability so monthly demand is suitable for rudimentary calculations. A worked example of the calculation of the volume ratio $\frac{production\ volume * cycle\ time\ of\ product}{production\ time\ of\ one\ FTE}$ is added in Appendix D.

Because the average R&O demand takes 8.3 full time operators, it is ranked as high volume. The other products in OEM assembly require less than one operator and are ranked as low volume. Subassemblies correspond to the OEM products and take even less time, so are also of low volume. For the new Scroll Compressor the volume dimension is still unknown. Because designing the product is not yet complete, the expected cycle time to produce that product is unknown.

Material Handling system
In Aeronamic's case, no automated handling system is currently present, and operators will continue to transport the materials manually with trolleys in the foreseeable future. As a result, there are no restrictions on which directions materials can flow.

Allowed flows for parts
Backtracking is allowed, but as outlined in Section 2.2 it should be reduced to a minimum. Cross overs are also allowed up to a certain extent. What must be prevented according to the Aerospace regulations EASA (2011), is mixing up of new and used parts. A Load Compressor part which has been repaired may never end up in a newly assembled Load Compressor. That means used parts may not cross over to OEM, but new parts crossing over in the other direction to R&O is fine. To make matters more complex, complete products, e.g. a fully assembled LC, may cross over amongst each other, as long as used parts do not enter new products. In conclusion, all types of flow layout are allowed. The only restriction is that used parts must be kept separated from anything that is new.

Number of floors
There is only one floor to consider so multi floor layout concepts are not applicable.

Facility Shapes
The facility shape is also a given constraint, so facility shapes are irrelevant as well.

Pick-up and drop-off locations
It is unnecessary to discuss pick-up and drop-off locations for R&O's processes because of the constraint that the location of the Expedition department is fixed. The R&O process always starts and ends at Expedition so both pick-up and drop-off are fixed. For OEM, drop-off is also fixed at Expedition, but pick-up of the process begins at the Inventory Storage System. This means there is freedom to choose the point in the facility where the OEM process starts.

3.3 Possible conceptual layouts

Only relevant layouts for Aeronamic are discussed here, so for a comprehensive overview of all resulting types of layouts from the aforementioned factors, the reader is referred to the survey by Drira, Pierreval, & Hajri-Gebouj (2007).

Three general organisations are possible according to theory. The fixed position layout, where the transformed resource stays in the same position and transforming resources are brought to it, is suitable for one-off projects and products that cannot be moved. The products produced at Aeronamic are quite small and easily moved using trolleys. They are also produced over a long period of time. That means the fixed position layout should not fit. The functional layout groups processes or resources with the same function together and is generally suitable for facilities that produce a wide variety of products. The product layout is suitable for high production volumes and a low variety of products. Facilities are organised according to the sequence of the successive manufacturing operations. It is well known from its use in the automotive industry. The youngest layout organization is the cellular layout, which is essentially a compromise between the functional and product layouts. Resources are grouped into cells to produce families of similar products. The extra challenge of cellular layouts is that the designer then has to decide on a layout within the cells.

Moving on to the four flow layouts, whose applicability depended on the material handling system and the allowed flows for parts discussed earlier, are depicted in Figure 6. The arrows show the possible directions for the flow paths. The single row layout is for products with flow paths along a line of stations. The flow only travels along the line and can visit any station along that line. Multi-rows are used when products flow along separate paths. The loop is best used when products visit stations several times. Open-field layout is the free flowing layout without restrictions to how parts flow. The multi-row layout, in which products flow in multiple disparate rows is the only allowable option for the Aerospace Production Facility as a whole, because of the constraint that used R&O- and new OEM parts must be kept separated during production. The other three layouts could all cause a mingling of parts entirely or at some point along the flow. A row for R&O and a row for OEM result. However, within these disparate rows of R&O and OEM, one can choose any flow layout that best suits their particular process characteristics. Note the similarity here with the discussion on layouts organisations.

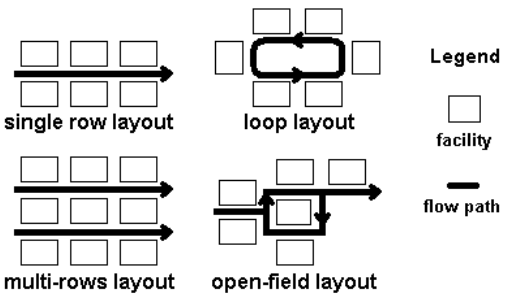


Figure 6: Flow layouts

Layout type	Single row layout	Multi-row layout	Loop layout	Open-field layout
Fixed Position	X	X	X	X
Functional	X	X	X	✓
Cellular	X	✓	X	✓
Product	✓	✓	✓	X

Table 3: Layout organisations vs. Flow layouts

The flow layout and the layout organisation also affect each other's applicability. E.g., a fixed position layout excludes any flow layout because a product remains in the same position. The functional layout generally requires an open-field layout because a characteristic of this layout is that flows cross over occasionally. Regarding the APF, that implies a functional design for the entire facility is difficult because that is exactly what must be prevented. The cellular layout fits with multi-rows, and open-field layout because although they separate product groups, some crossing over between cells is possible if needed. Loops are theoretically possible but in practice cells will hardly ever be placed such that the little flow between cells is a loop. The production lines in product layouts fit with single row, multi-rows and loop layouts. Only open-field does not fit because product layout is designed to reduce inefficient crossing over of flows. Returning to the multi-row layout that is required for the APF, product- and cellular layouts fit that flow layout. This discussion of fits is shown graphically in Table 3.

The constraints of the current building imply that only the single floor and rectangular facility is to be considered. Regarding the pick-up and drop-off points, they are fixed for R&O but OEM's pick up points are free to choose.

3.4 Choice of conceptual layout

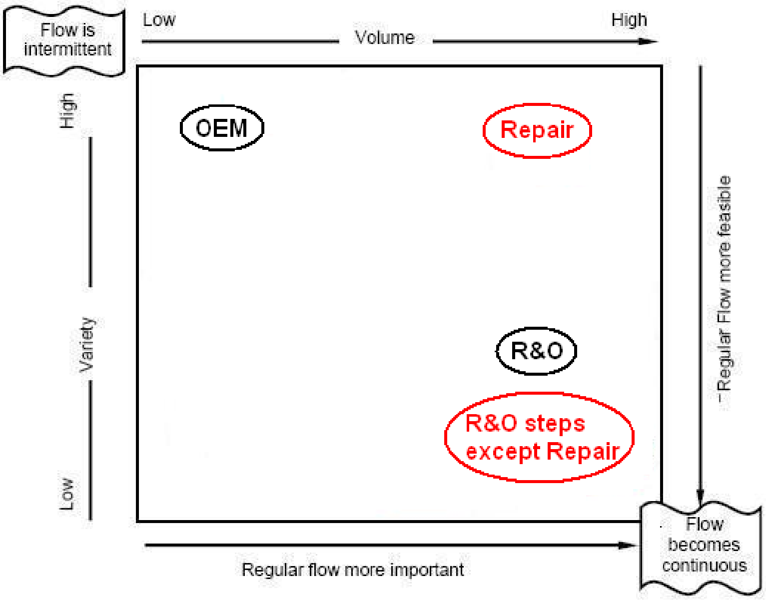


Figure 7: Volume variety dimension for Aeronamic
Source: Adapted from (Slack, Chambers, & Johnston, 2007)

When examining the volume-variety dimension for the products in the APF, one immediately notices the difference between the R&O and OEM departments. Figure 7 shows them in the black balloons. R&O shows higher volume with little variety in the jobs whilst the OEM section has lower volumes of several completely different products. Their best layout fits are therefore a product- and functional layout respectively. These two different layouts can be achieved at the same time by using a cellular layout. The similar processes are grouped into one area called a cell. One cell is then responsible for R&O with the other performing OEM. Within these specific areas, a new choice for a layout organisation can be made, thus enabling product layout for R&O, and functional layout for OEM. Recall that the current layout also features the two cells, and these have become separate units as a result of the wall of Inventory Storage Systems (ISS). Is cell layout then really a good idea? Yes it is. Not the cell layout, but the wall of Inventory Storage Systems caused the separation of teams, so by placing the ISS differently, this can be prevented from happening again. The cell layout also fits with the requirement for a multi-rows flow layout, since it is well suited to keep used and new parts from crossing over during production.

Within the proposed R&O cell, all process steps are low variety and high volume, except for the Repair step, which has high variety and high volume. These differences are illustrated by the red balloons in

Figure 7. Please note that the placement of the red balloon below the black R&O balloon does not imply a difference in their volume variety dimensions. From the figure, a product layout with dedicated stations for each step seems a good idea in general for R&O, but this does not fit with the Repair section's variety. Unfortunately, from Figure 5 one cannot conclude which layout should be applied in this specific case. The choice between a product layout with all repair equipment in a line or a functional layout must be made differently. Therefore, the generally known advantages and disadvantages of the layout organisations will be examined next to make a choice. These are given in Table 4, where red text indicates poor performance, green text indicates good performance and black text indicates average performance.

	Functional layout	Product layout	Cellular layout
Flow length	long	short	medium
Tot. Prod. Time per unit	long	short	medium
WIP	high	low	medium
In process inventory	high	low	medium
Resource utilisation	high	low	medium
Production planning	complex	simple	medium
Flexibility	high	low	medium
Operator skill required	high	low	medium
Job character	high task diversity	repetitive	team mentality
Job satisfaction	high	low	high
Supervision possible	specialised	general	general

Source: Adapted from (Francis, McGinnis Jr, & White, 1991)

Table 4: Advantages and disadvantages of layout organizations

The R&O Repair section houses different machines, which are not necessarily used for every Production Order because they all require different repairs. A product layout is not suitable, because resource utilization is generally low and it does not offer the required flexibility in use. The functional layout does, and its major disadvantages of high WIP and high inventory are negligible because the Repair section will only be a special cell within a bigger layout, dependent on earlier steps for its work. WIP and inventory should therefore never be higher than at other stages. Length of flow will not be a problem either because this cell can be small. The choice is thus made to introduce a cell within a cell, i.e. a Repair section arranged in a functional layout, within the R&O cell that has a product layout.

The OEM cell should have a functional layout according to theory. Its current layout bears resemblance to a fixed position layout, albeit with some functional elements. Every product has a dedicated workbench for assembly with all its tools. Materials are brought to the bench and the products are moved only for operations that cannot be located at the workbench because the equipment is too large or expensive. Switching to a functional layout, would mean viewing assembly as a function. Is this actually possible or do all products really justify having a dedicated workbench?

The workbench ratio in Table 2, indicates how many workbenches are required to perform a month's work on a given product. The difference in values with the operator ratio arises from the fact that a workbench can be utilised 100% of the time, whereas an operator cannot. See Appendix D for the calculations. Table 2 shows that 2.63 workbenches are required to perform all current OEM operations including subassemblies, with current cycle times and volumes, if no waiting occurs. Four FTE are present at OEM and for the six products, seven workbenches are available. This means that theoretically, the workbenches are being used for value adding activities 38% of the time. The only conclusion can be that having dedicated workbenches is unnecessary. Especially when looking at products like the ACM, Tay 2000 S and Tay 2000 AFV, one sees that with ratio's of 0.27, 0.18 and 0.13 these workbenches are unused more often than not. Whether adding two products to OEM's portfolio will change the low workbench utilization much cannot be said, because the expected LC 400 volume is small and most data on the Scroll Compressor is unknown.

It was already argued that the products assembled at OEM are not sufficiently large, heavy or immobile to justify fixed positions. Another consideration is that tracking the stages of WIP is generally more difficult in a functional layout than in a product layout. It is important to realise that this is influenced by the sequence of operations, which at OEM is fixed for every product in assembly instructions. That actually makes tracking WIP stages easier, because a product will only be at the next WIP stage once it is ready for that operation. If this were not the case and the operations could be performed at any time, then it would be more difficult to make WIP stages visible. Cleverly positioning elements to guarantee a progressive flow can resolve this concern, as will be shown in Section 5.1, where the issue of visible WIP stages will be revisited. All in all, the choice to redesign the OEM cell to a functional layout is justified. Now, it is time to move on to the flow layouts of the specific cells.

Looking at the R&O cell specifically, pick-up and drop-off are at the same location, namely Expedition. Ideally, parts only pass through the workstations once, excluding loops. A single row layout in U-shape makes most sense. This also fits with the product layout as can be seen in Table 3.

For the OEM cell, pick-up is free to choose and drop-off is fixed at Expedition. Furthermore, products share varying resources like the measurement table and balancing bench. Open-field flow offers the greatest flexibility in the positioning of these resources, which is why it is generally required for a functional layout. Therefore, open-field flow will be considered in OEM's case.

3.5 Conclusion Chapter three: conceptual layout

To conclude this chapter, the progress made within the research framework up to now is given in Figure 8. Theory on layout concepts and process data from the company were used for the answering of research questions 2.1 and 2.2 respectively. Comparing the theory to the process data with the criteria and constraints in mind, resulted in a number of possible layout concepts. This covered research question 2.3. A cell layout with a product- and functional layout was finally chosen as the best conceptual layout for Aeronamic, completing research question 2.4 and this part of the research.

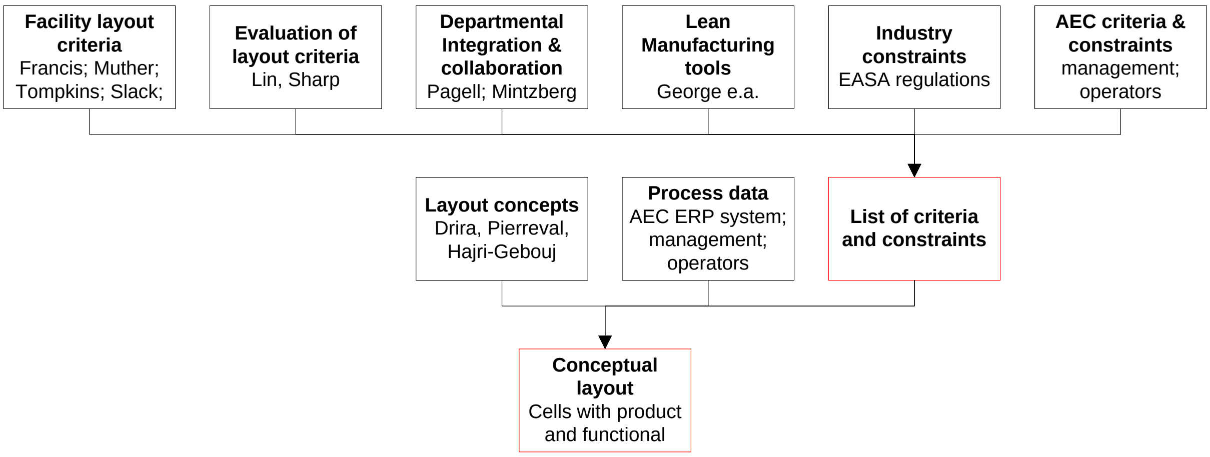


Figure 8: Progress in research framework after Chapter three

More comprehensively, the detailed generation of alternative layout solutions for the Aerospace Production Facility will be done with a cell layout of two cells. The R&O cell will be a product layout with a U-shaped single row flow. Within that product layout, the Repair section will be a cell with a functional layout. The second cell, OEM, will be redesigned as a functional layout in which flow may be open-field so as not to restrict the options yet. An illustrative drawing, that only serves as an illustration of the concepts and does not in any way resemble a solution, is found in Figure 9 on the next page. The pick-up and drop-off locations are marked in yellow. In the OEM cell, multiple stations are coloured yellow because its pick-up location is free to choose. The fixed departments from the constraints and the area with the planned expansion are also included.

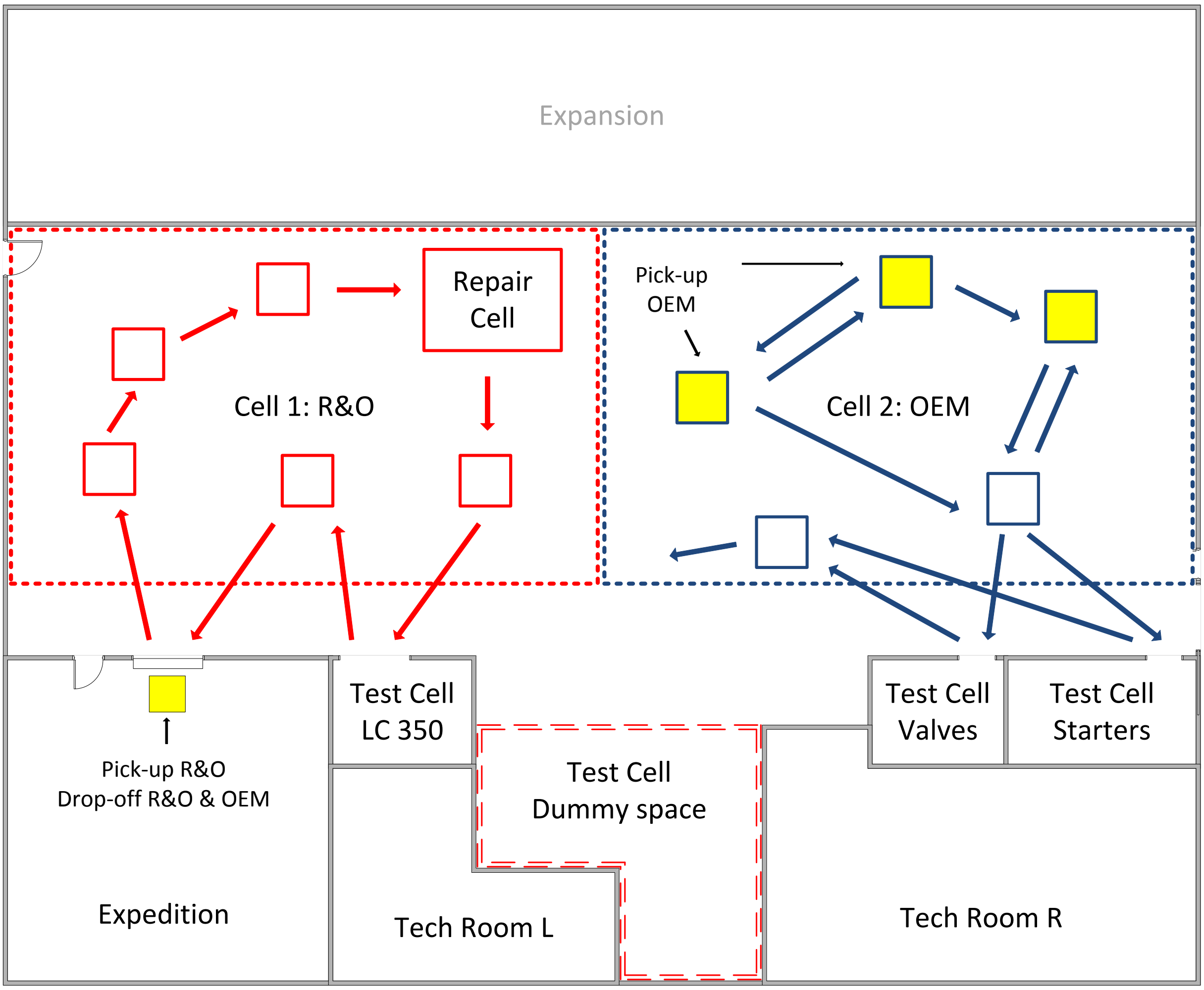


Figure 9: Illustration of the conceptual layout for the APF

4 Layout design method

The forthcoming chapter treats design methods for generating the alternative layouts from the concept chosen in the previous chapter. Their ability to provide solutions is reviewed to determine the most suitable method for Aeronamic. Finally, a decision making method is chosen to evaluate alternatives. That corresponds to research questions 3.1 till 3.3 and 4.1. Unless stated otherwise, this chapter is based on three reviews of existing literature on generation of layout designs by Kusiak & Heragu (1987), Tompkins, White, Bozer & Tanchoco (2003) and Drira, Pierreval & Hajri-Gebouj (2007).

4.1 Design methods in the literature

Over the years, many 'layout design procedures' have been developed by different authors, e.g. J.M. Apple, R. Muther and R. Reed Jr.. These methods all boil down to the same principle of collecting data, analyzing (flow) relationships and space requirements, generating alternative layouts, measuring performance and then detailing the most promising alternative(s).

The choices made in Chapter three for cell layout, and product- and functional layout within the cells, imply methods geared towards those layout organizations are needed. In a review on layout design for cellular layouts by Hassan (1995), the following three steps were identified; grouping product families into cells, the arrangement of machines or workstations within the cell and finally determining the configuration of cells in relation to each other. These steps were found to be interchangeable. Also, the third step is found to be essentially equivalent to a functional layout problem and so similar solution methods can be used. The difference is that intercellular flow is generally simpler than between functional blocks. Regarding the placing of workstations in a product layout and functional blocks in a functional layout within the cell, the design methods discussed here generally solve both problems.

Recall from Section 2.2 that the criteria originated from both technical and social requirements, working as one team being an example of the latter. Hyer, Brown, & Zimmerman (1999) developed a Social Technical Systems (STS) approach to cell design to consider these requirements simultaneously, because these factors influence each other. They identified several principles that are important for both the social and technical aspects of a redesign. First of all, the design process must be compatible with the social goals of the redesign. In this project, where flexibility and working as a team is the social goal, the design process of the technical system should include the team working together. The layout design should be specified to the bare minimum, so the employees can design the cell to their ideas. For this to happen, operators need to be given responsibility for their processes, but also the skills to bear these responsibilities through training. Furthermore, the social structures at the company should support the layout, because without a fitting structure, a layout change will not achieve social goals on its own. Finally, employees always need to be shown how they benefit from the change to motivate them towards contribution. It is obvious that the STS approach places a lot of emphasis on the human factor in layout redesign.

In contrast to STS, most scientific research on layout design focused on the technical aspects only. The problems considered were quantitative formulations to minimise material handling costs between departments or qualitative formulations to maximise desired adjacency of the departments. Computer aided layout design to solve these layout problems was heavily discussed among researchers in the 20th century, but the social factors were rarely considered in these discussions. Despite all the effort, Cambron & Evans (1991) have shown that computer algorithms do not outperform human designers in designing good layouts when considering multiple criteria. They are considered to be useful tools for idea generation, gaining insight and increasing productivity of the designer nonetheless.

A review of the most popular computer algorithms for layout generation, including their general working and their strengths and weaknesses is included in Appendix E. This review is far from comprehensive but gives an indication of what is available in the academic world. If a higher level of detail is required, the three reviews mentioned at the top of this page and the original works on the algorithms can be consulted.

4.2 Design and decision method for Aeronamic

Continuing towards a design method for Aeronamic's APF, the systematic layout design procedure will obviously be adhered to. Data on flow relationships and space requirements will be presented in the next chapter, after which alternative layouts will be generated, scored, improved and detailed. The generation and scoring of- and decision making on layouts is most interesting to examine now.

Because of the presence of technical and social criteria, an approach catching the benefits of STS is desirable. That means operators need to be involved intensively in the design process, and that they should work on the design as a team. Another resulting requirement is that layout designs should not be too far detailed before operators offer their inputs. The emphasis on the human role in design from the STS implies that layout generation is not to be performed by a computer algorithm, but predominantly by people.

Scientific research also supports this, not in the least because of the presence of multiple criteria. Kumara, Kashyap, & Moodie (1987) e.g., call for interaction between computer aided design methods and human users because algorithms are less able to judge multiple criteria than users. That interaction is exactly where a computer algorithm can be of value. As shown in Section 4.1, it can be a useful tool to evaluate layouts and improve them. Consequently, the computer algorithm CRAFT will be used as an evaluation and improvement tool for the layouts that were developed by hand.

CRAFT (Computerised Relative allocation of Facilities Technique) as developed by Armour & Buffa (1963), is an algorithm that uses pairwise exchange of adjacent departments to improve an initial layout. An initial solution thus has to be provided by the user, with the numbered blocks in Figure 10 representing departments. CRAFT calculates the weighted rectilinear distance travelled by materials from one department centroid to another department's centroid and sums these values for all departments to obtain the total layout score. Its objective is thus to minimise material handling costs. If an exchange of two adjacent departments offers an improvement, e.g. exchanging departments one and two, the exchange is made. If no such exchange exists, the algorithm terminates.

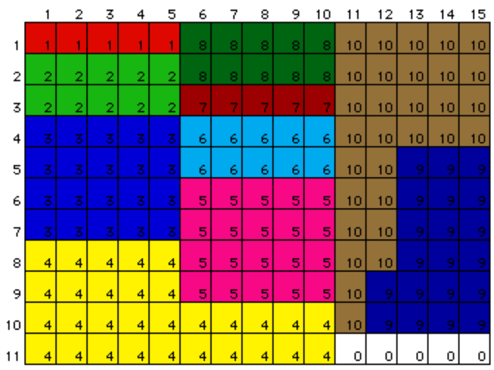


Figure 10: Example of CRAFT

CRAFT is suitable as an evaluation tool because its objective is to minimise material handling costs, which also works towards improving the flow as is desired in this research. The algorithm is also dependent on the user for initial solutions, making it extremely suitable to evaluate the layout solutions generated with the help of operator and designer input. Any flaws in the design regarding flow length can be found by the algorithm and improved. Finally, CRAFT is well able to deal with fixed elements. Because of the fixed locations for e.g. the test cells, this is an important feature. A more elaborate motivation of the choice for CRAFT over other computer algorithms is located in Appendix F.

Moving on to the decision making process, to assess the final alternatives a decision making method for multiple criteria is required. In the literature, the Analytic Hierarchy Process (AHP) is very popular and has proven capable of being an effective decision making tool for layout problems in studies by Cambron & Evans (1991) and Yang & Kuo (2003). "AHP employs two core principles of structuring the decision problem into a hierarchy of goal, criteria and alternatives", and making pairwise comparisons to establish relations between criteria and alternatives within the hierarchy (Saaty R. , 1987). The tool allows for errors and inconsistency in judgement and deals with them formally. Structuring the decision problem and simplifying to pairwise choices make AHP easy to apply. This, along with its proven track record, not least in layout problems, makes AHP a good decision making tool for this research.

For the execution of AHP, Aeronamic's management will be asked to compare the layout performance criteria from Chapter two in pairs to determine their relative importance. The layout alternatives' performance will be judged by the designer to avoid initial preferences from management influencing the decision making process. The best performing layout is chosen for full detailing and recommended as the new layout.

4.3 Conclusion Chapter four: design process recap

To complete this chapter, and with it the theoretical framework for this report, this is the layout development process in short. The process is started by generating many ideas in brainstorm sessions with operators from both R&O and OEM. These ideas are then geared towards the goals and preferred concepts. With the relevant data on material flow and space requirements, drafts are created and quickly evaluated with CRAFT on their performance. A feedback cycle with the operators and management will be performed to ensure sufficient involvement is achieved to obtain good solutions and support. Based on the feedback, the most promising layout alternatives will be fine tuned. The above methods are chosen because Aeronamic's layout problem is a multi criteria problem with a strong social component. To arrive at the recommended layout solution, the Analytic Hierarchy Process will be used to make a choice between the generated layout alternatives. Preferences will be determined by consulting Aeronamic's management.

The entire design process is now fully developed and Figure 11 shows it within the completed research framework. This is the last time it will be shown, because no new theory will be introduced in the remainder of this report.

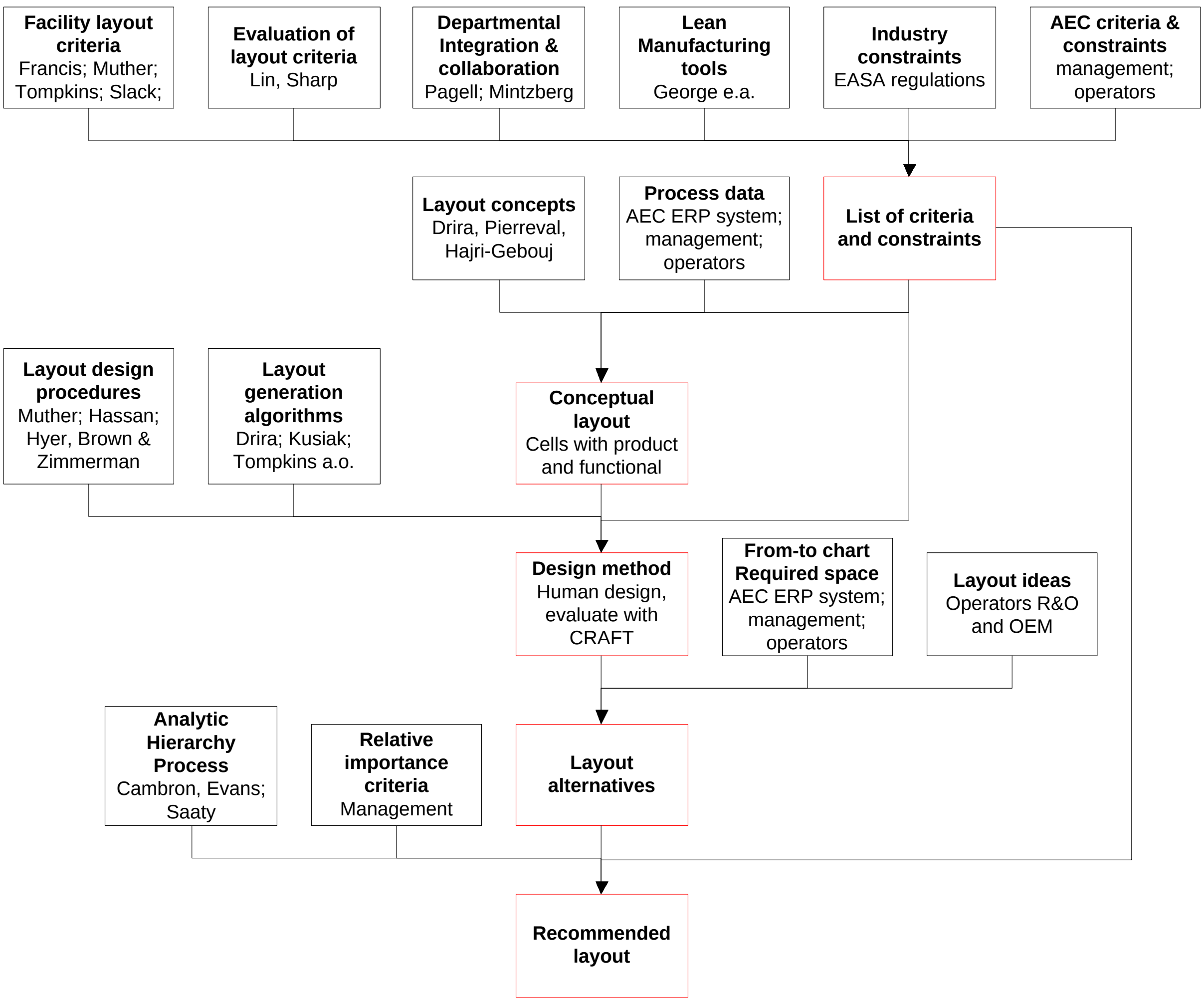


Figure 11: Design process within research framework

5 Layout design alternatives

The following chapter treats the detailed generation of alternative layout solutions for the Aerospace Production Facility. Recall that this is done with a cell layout consisting of two cells. The R&O cell will be a product layout with a U-shaped single row flow. Within that product layout, the Repair section will be a sub cell with a functional layout. The second cell, OEM, will be redesigned as a functional layout in which flow may be open-field.

First, the required elements are discussed, along with their required space in the facility. Then the from-to chart and REL chart are presented, after which the preliminary design concepts are discussed briefly. Preliminary evaluation sessions with management and the operators resulted in six final layout alternatives, and so these will be presented to conclude this chapter.

5.1 Required elements

R&O's elements

From the flow charts drawn up to gain insight into the production processes, and from discussions with operators and management many required functional elements were determined. In the R&O cell, space is required for the process steps Disassembly, Visual Inspection, Findings Report, Repair, Assembly R&O and Final Out inspection. Cleaning and Non Destructive Research (NDR) are other R&O functions but these have fixed locations. Space is finally required for the storage of boxes for Load Compressors, storage of jobs waiting for disassembly, storage of jobs waiting for customer approval and one Inventory Storage System (ISS)

OEM's elements

In the OEM cell, seven ISS need to be placed, two with parts for compressors and five ISS with parts for all the other products. Assembly space for the Load Compressor 350 and 400 series and for the other OEM products is also required. These two functions are immediately needed, whilst space for the upcoming Scroll Compressor also needs to be reserved for when it enters production. A good reason to define the current assembly processes as separate functions, is because the Load Compressors require a different test cell than the Starters and Air Flow Valves which belong to the 'other OEM' category. These test cells are located at some distance from each other, so placing the two assembly functions in different locations close to their respective test cells might benefit flow length. Another reason to name assembly space for compressors separately is that from Table 2, the LC's and its subassemblies can use a workbench almost completely by themselves. Because of the separation, Assembly Comp is henceforth defined as the assembly area for the LC 350 and LC 400 series, Assembly OEM is defined as the assembly area for all OEM products except the compressor products, and Assembly Scr C is the space reserved for the Scroll Compressor.

Assembly OEM design

The idea developed in Chapter three was that the Assembly OEM function should not have dedicated workstations for each product any longer. If no dedicated workstations are available for products, then what should Assembly OEM look like instead? A generic assembly station needs to be available, at which any product can be assembled. Several of these stations are then required to offer sufficient assembly space to meet total demand. However, there is one major difficulty. Each product at OEM requires specific tools to be assembled. A generic workstation would then require all tools present to be able to support all product assembly processes. Not quite, as a flexible workstation can be created by only bringing product specific tools to the bench when they are needed.

5S dictates that tools need to be available to the operator when they need them, where they need them, and that the operator must be able to see if all tools are present in the blink of an eye. When not required, the tools are to be stored away. Currently, Aeronamic uses shadow boards to store tools in a visual manner, which makes it very easy for operators to see if everything is available. For the reason mentioned above, these shadow boards cannot be attached to a workbench.

Mobile shadow boards, called ‘tool trolleys’ from now on, are the perfect solution. These tool trolleys can be moved to the workbench to change a flexible generic assembly station into a station capable of assembling a specific product. Once assembly of a product is finished, the tool trolley is stored away and room is made for a different tool trolley. The basic idea is illustrated in Figure 12. This way, the flexible assembly station can be used to assemble any product. Flexible workstations which can be equipped with the required tooling at any time, will thus enable Assembly OEM to operate as a functional element in the layout.

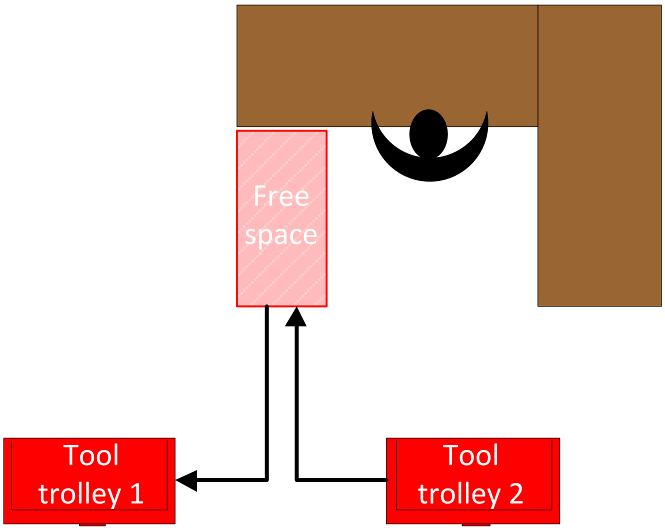


Figure 12: Flexible assembly station OEM

Looking back at Table 2, four flexible assembly stations will easily suffice to meet the aggregated OEM demand for 1.71 workbenches. Four is chosen because there are four OEM operators presently employed at Aeronamic. In the event that four different OEM products need to be assembled simultaneously, all four will have a workbench to assemble at.

New elements Final Out OEM and Finished goods OEM and R&O to track WIP stages

Now, turning our attention to the objectives of a clear flow and visible WIP. One cause for the current layout to perform badly on these is frequent backtracking to stations. To illustrate, the Air Cooling Machine (ACM) tracks back to the assembly workstation no less than five times. That is partially because some operations have to be performed with other equipment. That cannot be helped, but the ACM also goes back for the Final Out inspection and stays on the assembly bench to wait for shipment after completion. That is three WIP stages in one location. This makes it unclear in what stage the product is in and has the extra disadvantage that it keeps the workbench occupied. To prevent this in the new layout, a new station for Final Out inspection and storage locations for Finished products will be created at OEM. The assembly stations will then be free for value added work and the products will flow more towards a destination, being Expedition for shipment to the customer. A finished goods storage is also added for compressors for the same benefits.

Common Machine section

Another new element is a ‘Common Machine’ section. The balancing bench, measurement table and the oven are used for multiple products, as can be seen in the process flow charts in Appendices B and C. These pieces of equipment were located in different locations and products were brought to them. Their seemingly random placement before the redesign caused long travel distances and a messy flow. Grouping these machines into a ‘Common Machine’ section and placing this section centrally between the assembly areas will greatly reduce the length and messiness of flow.

Elements in constraints

Several elements are constrained to their current locations. These are the Test cells, Technical rooms Cleaning and Expedition. The area in between the test cells is to be reserved for a new test cell.

Inventory storage

In the current layout, there is insufficient space for inventory at OEM (parts, packaging materials), meaning inventory is lying around the production floor. Buffers of WIP in the process is undesired because this is not lean, but there is a need for storage space for these input materials. This storage space for OEM is thus the last desired element.

Equipment NDR and Repair section

Many pieces of equipment which are currently positioned across the APF, will go in the new NDR and Repair areas. These are Magnetic Particle Inspection-, Frequency Testing-, Eddy Current Testing-, Ultrasonic Testing, Actuator Testing and Thermal Testing equipment for the NDR area and a grinding machine, welding station, oven, press and air extraction area for the Repair section. These elements will be assigned to the respective areas during detailing of the chosen layout, but not be considered yet for the designing of different layout alternatives. Area requirements for NDR and Repair will suffice. To give an overview, all functional elements and their space requirements are presented in Table 5.

Functional elements	Short name	New	Fixed	Location	Space required (m2)	Space required (m3)
Fixed elements						
Expedition	Exp	No	Yes	current	127	
Test cell LC 350	TC LC	No	Yes	current	19	
Test cell AFV	TC AFV	No	Yes	current	18	
Test cell Starters	TC S	No	Yes	current	25	
Technical Rooms left	Tech L	No	Yes	current	56	
Technical Rooms right	Tech R	No	Yes	current	113	
Cleaning	Dum Cl	No	Yes	current	254	
NDR	NDR	Yes	Yes	expansion	85	
New test cell + tech room	Dum TC	Yes	Yes	Tech L < .. < Tech R	55	
R&O cell						
Storage boxes Load Compressors	St Box	No	No		11	
Storage waiting for disassembly	St Dis	No	No		5	
Disassembly	Dis	No	No		30	
Visual Inspection	VI	No	No		19	
Findings Report	FR	No	No		15	
Repair	R	No	No		57	
Assembly	A R&O	No	No		28	
ISS R&O	ISS R&O	No	No		8	
Final Out inspection R&O & Compressors	FO Comp	No	No		5	
Finished goods R&O & Compressors	Fin Comp	Yes	No		4	
Storage waiting for customer approval	St Cust	No	No		10	
OEM cell						
Assembly LC 300 & LC400	A Comp	No	No		18	
Assembly rest OEM	A OEM	No	No		35	
Reserved for Assembly Scroll Comp	A Scr C	Yes	No		18	
Common machine section	CM	Yes	No		14	
Final Out preparation OEM	FO OEM	Yes	No		11	
ISS LC 350 & LC 400, Scroll	ISS Comp	No	No		24	
ISS rest OEM	ISS OEM	No	No		60	
Inventory storage parts & packaging OEM	St OEM	Yes	No		-	80
Finished goods OEM storage	Fin OEM	Yes	No		10	
Total space required minus aisles					1134	
Total space available					1476	

Table 5: Space requirements functional elements

Next to the space requirements, the flow relationships between elements and the desired adjacency of elements are also important. Without them, CRAFT would not function and the criteria for minimal length of flow, minimal backtracking and crossovers of flow, and the high proximity of departments requiring informal communication cannot be evaluated. The from-to chart was set up using data from Aeronamic's ERP system ISAH and an interview with management. It is a matrix that gives the expected monthly flow of materials between elements. One unit of flow generally represents one product moving from one element to another. In case of batch movement, the batch is counted as one flow, because any batch of products is moved using the same trolley. The from-to chart is presented in Appendix G because of its size and because a short glimpse suffices to understand it.

The REL chart in Figure 13 gives the desired adjacency rating between pairs of departments. When adjacency is desirable, this means that it is desirable to enable informal communication between people manning the departments. Flow distance is already accounted for by the from-to chart, so this need not be taken into account when determining this REL chart. The ratings were determined in conjunction with the operators, because they could pinpoint where informal communication would be beneficial. The desirability ratings are shown in red and mean the following:

A = Absolute importance
E = Essential importance
I = Important
O = Ordinary importance
U = Unimportant
X = negative importance.

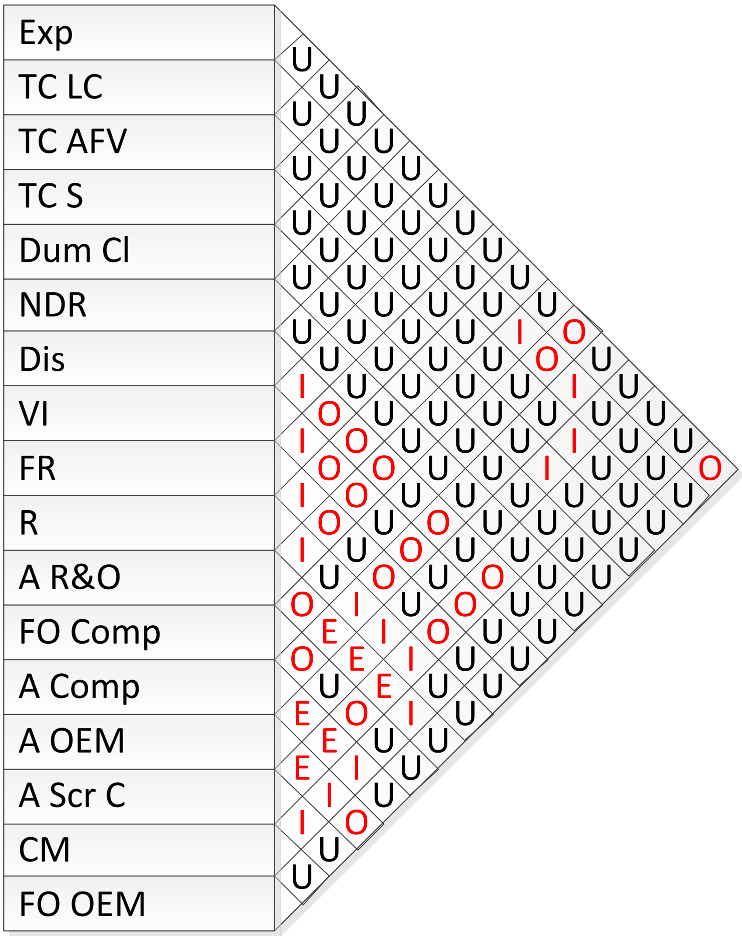


Figure 13: REL chart Aeronamic

The reader may also notice that less departments are included in the REL chart than in the from-to chart. The reason for this is that the ISS, St Box and St Cust e.g. are not departments where people work. These are elements which must be present for storage of parts, but operators will not be working there. Communication between these elements is thus not required, so these elements can be excluded from the REL chart.

5.2 Cell design concepts

After having determined the functional elements, an extensive brainstorming session was held with operators to generate many ideas for the new layout. The session's topics varied between methods to save space in general, how to place big elements to avoid separation, what the flexible assembly station should look like and workstation design. The relative positioning of functional elements was also discussed to see what the operators' initially preferred configurations were. The following ideas were the most interesting and/or useful for the design process.

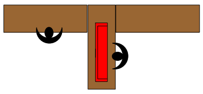


Figure 14: T-bench

- Space at workstations can be saved by sharing bench space. Placing two workstations adjacent to each other with one common bench in between to form a T-shape like in Figure 14, means less space is needed to house the two stations' shadow boards because they are both on the shared bench.
- Storage of inventory can be done in high racks or on a second floor level to save floor space. Storage in high racks can be a good solution since 80 m^3 of storage space is required at OEM.
- Placing big elements like the ISS on the edges of the facility will reduce the amount of boundaries causing separation of departments.
- Operators desire as much free space as possible at their workstations. The shadow boards, for all their advantages, do take up a lot of space. Removable or fold away shadow boards would leave much more free space. This idea coincided nicely with the mobile tool trolleys to enable the flexible workstations.
- L-shaped and U-shaped workstations will use less space than straight benches and improve operator productivity as well. Workstations should therefore be L-shaped or U-shaped.
- Place Repair in a closed off area in the expansion. This saves a lot of space in the APF and automatically solves the constraint of keeping the dirty repair process separated from the 'clean' processes

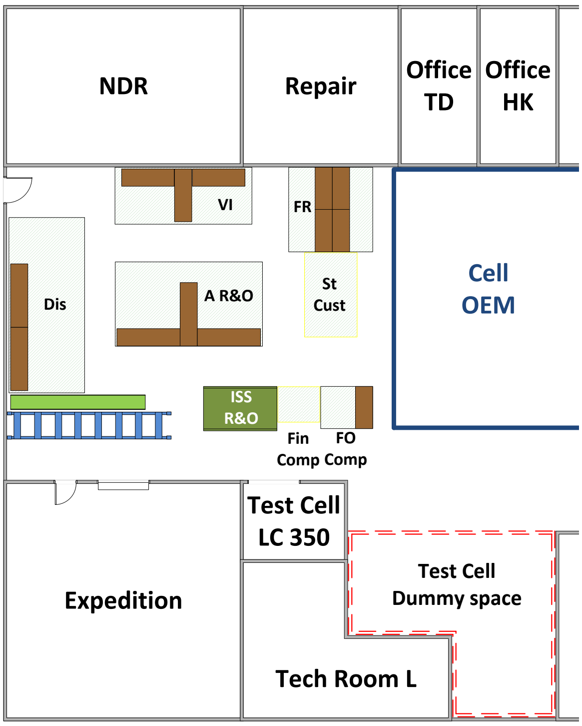
This last idea was of great significance for the remainder of the design process. Management agreed to place Repair in the expansion, next to NDR. The result was that Repair would still be close to the elements it had flow relationships with, but truly separated and without occupying a significant chunk of the space in the APF.

After this brainstorm session, several cell concepts were drawn up for both the R&O and OEM cells with the aid of the space requirements, from-to chart data and REL chart data. These concepts were entered in the CRAFT optimization procedure to see if CRAFT would find improvements. After finishing with the algorithm, the layout concepts were shown to the operators and management in feedback sessions to increase their involvement and obtain more suggestions for improvement.

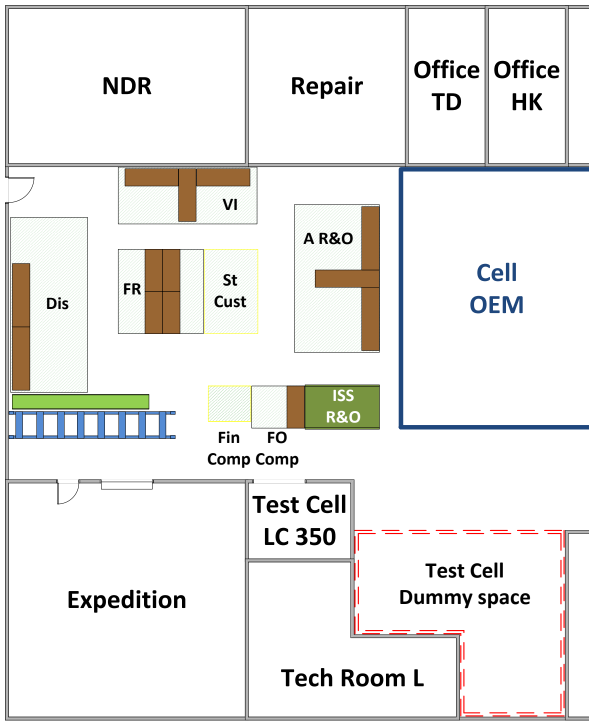
R&O cell concepts

Four different cell concepts for R&O were designed, all of which are shown on the next page. It can be seen that Repair is situated next to NDR in the expansion. T-shaped workbenches are also visible at VI and A R&O. Notice that VI has one bench less. Another noticeable feature of all concepts is that the ISS and the blue inventory rack are situated at the edges to obtain a more open and spacious feeling to the layout.

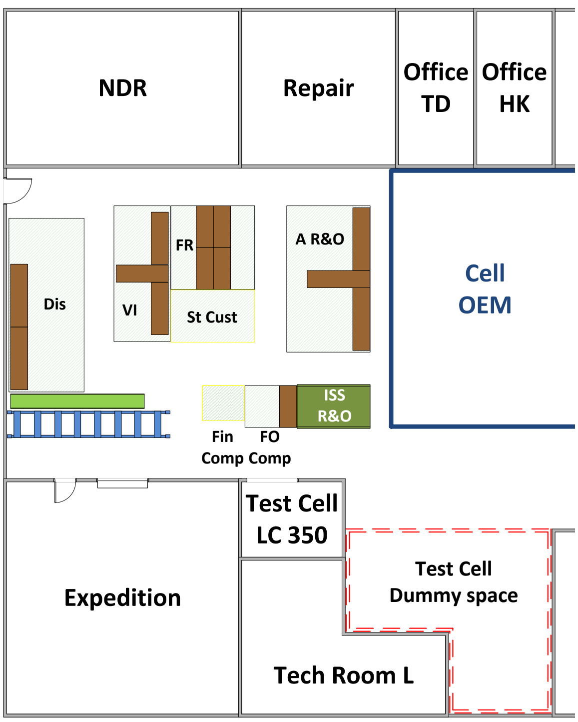
Concept A, which coincidentally looks most like the current layout, performed badly on CRAFT's distance measure. CRAFT's improvement was swapping Findings Report (FR) with Assembly R&O (A R&O) to place the latter directly beneath Repair for a big reduction in distance travelled. Concept A was therefore discarded as a solution and the other three with A R&O exactly in that position remained in contention. CRAFT's second improvement was to place Visual Inspection (VI) along the upper wall of the existing building in concept C for a reasonable reduction in distance travelled. The reasoning is that placing VI between Cleaning and Repair in a straight line minimises length of flow. However, because the improvement was not as drastic as for concept A, concept C was not yet dropped. CRAFT showed no further improvements.



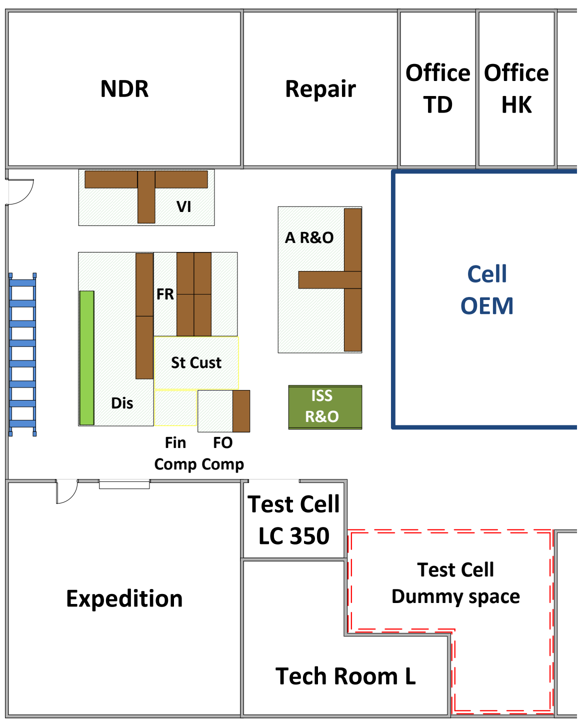
R&O cell concept A



R&O cell concept B



R&O cell concept C

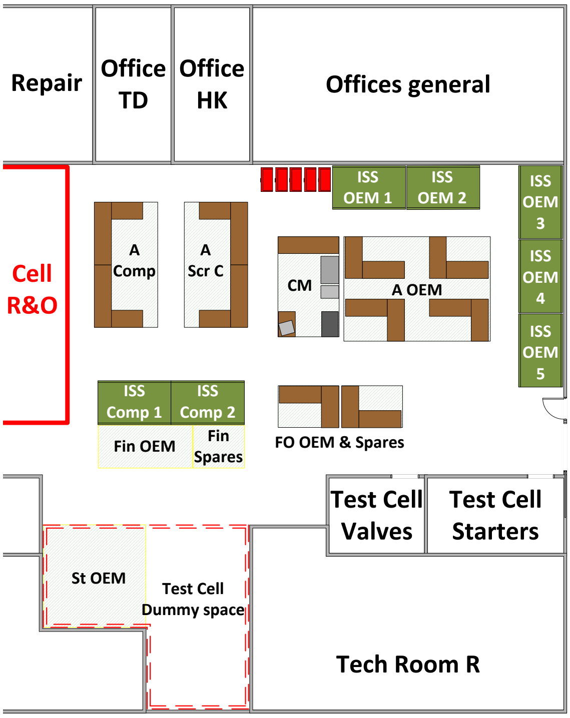


R&O cell concept D

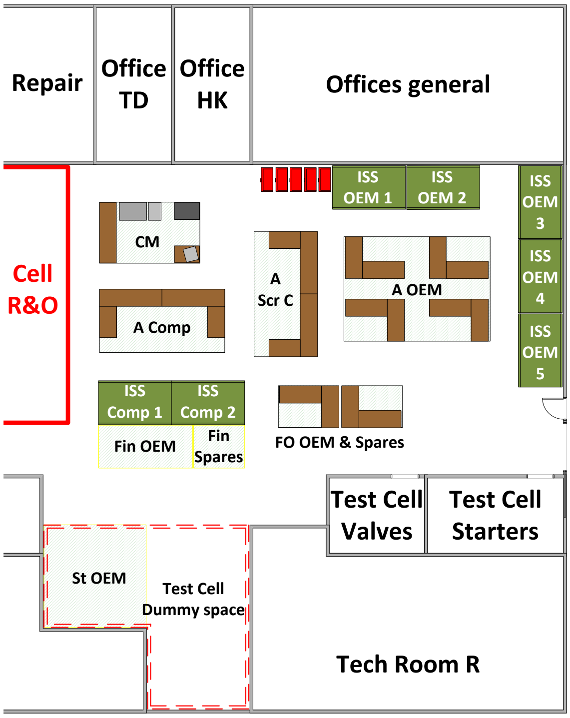
During the feedback sessions, concept B was the operators' and management's favourite. Concept C is not much different to concept B, but the operators disliked the straight aisle along the upper edge of the cell. They feared it would become a too convenient walking aisle for other employees, which could cause them much unwanted disturbance. Concept D was perceived to be a promising idea, since the high inventory rack (blue element) would no longer be located along the main aisle. However, a walking bridge is planned along the left edge of the cell. It is meant to link the offices on the first floor at the bottom of the APF to offices in the expansion. That unfortunately excluded concept D as a feasible option. Concept B and C were chosen to be examined along all the criteria.

OEM cell concepts

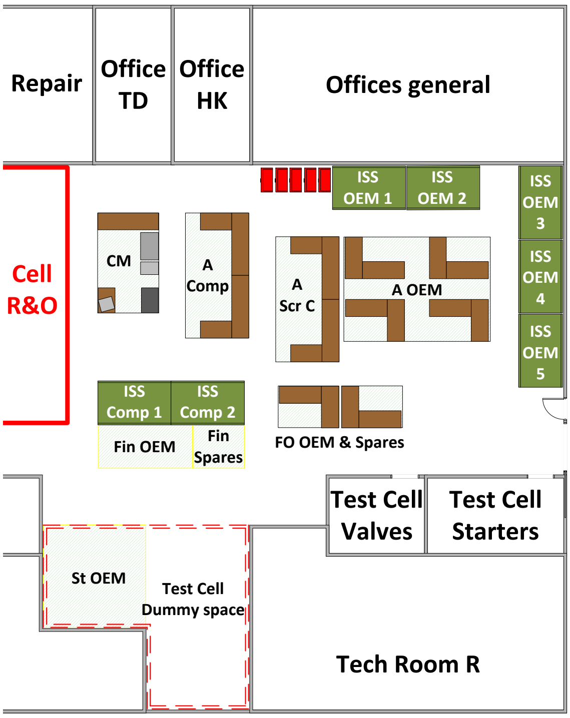
Below are five cell concepts for the OEM cell. Concepts A, B and C boast the flexible assembly stations (A OEM) and tool trolleys (red trolleys positioned at the top of the cell). When the idea for flexible assembly stations was first proposed, it was met with some aversion and resistance. To help the operators who initially opposed the idea see its potential benefits, two concepts were devised with dedicated assembly stations. These are concepts D and E and can be used for comparison. Note that the pick-up points at OEM are at the Inventory Storage Systems, where parts are picked when a production order is received. Pick-up and drop-off points will not be discussed further in this report.



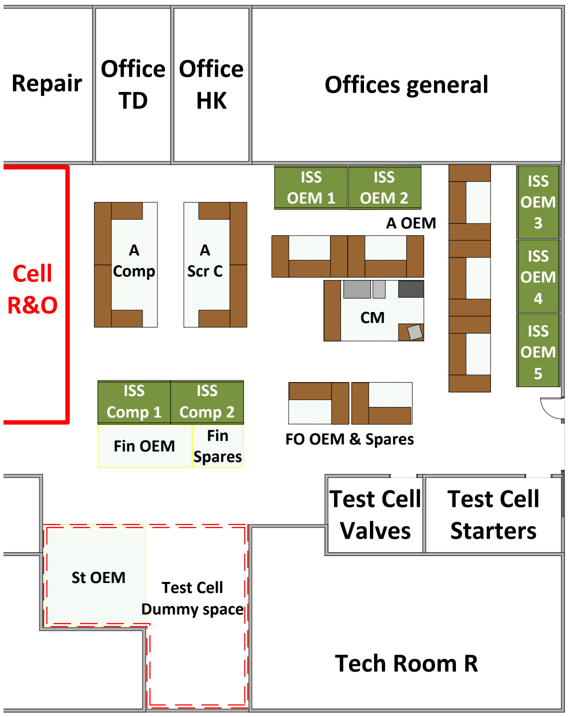
OEM cell concept A



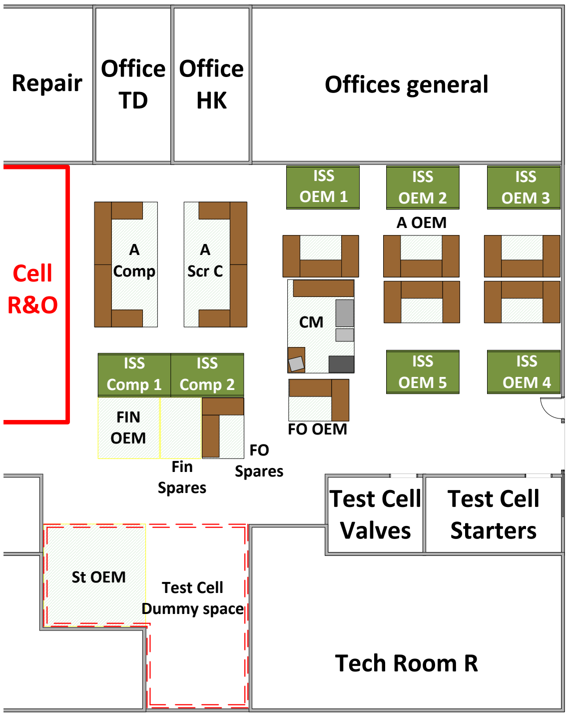
OEM cell concept B



OEM cell concept C



OEM cell concept D



OEM concept cell E

The largest chunk of the ISS needs to be placed in the OEM cell, no less than seven. In line with the ideas from the brainstorm, they have been placed on the edges of the facility in all concepts, wherever possible. The reason the two 'ISS Comp' are not placed on the edge is that they would block either the two offices TD and HK or the test cell when it is built in the reserved space. The 'ISS OEM' can be placed along the northern edge because the Offices general are not allowed direct access to the APF.

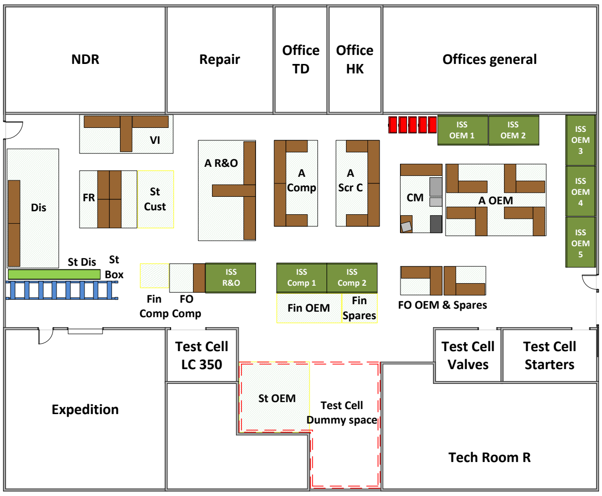
Cells A, B and C differ in their positioning of the Common Machine (CM) section. CRAFT ranked A and B as better than concept C. The feedback sessions gave the same result. Both the operators and management thought concept C was cluttered compared to the calmer appearance of A and B. Because they did not differ much otherwise, C is dropped. A and B continue to criteria evaluation.

The two concepts with dedicated assembly stations also performed reasonably in CRAFT, but that is mostly due to the fact that CRAFT uses rectilinear distances from department centroids. In reality, concept D should perform horrendously for flow length because of the dead end aisle on the right. Concept E would still be fine though because there are aisles in between each dedicated station.

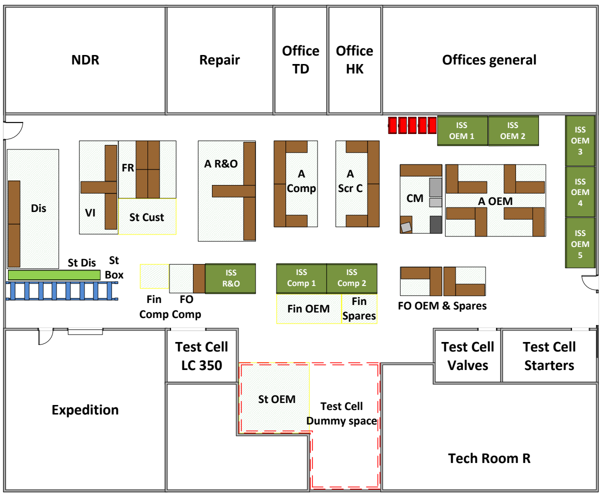
The two concepts also proved their worth in the feedback sessions. Having got more used to the idea of flexible assembly stations and seeing the difference in pictures, all operators agreed that the concepts with flexible assembly stations were better. They even went as far as to say concept D would hardly be an improvement. Concept E did not receive the same criticism but the response was lukewarm at most. The obvious conclusion was to drop concept D, but concept E will still be evaluated with all criteria. The reason is to irrevocably show that flexible assembly stations are the best option.

5.3 Conclusion Chapter five: from cell concepts to layout alternatives

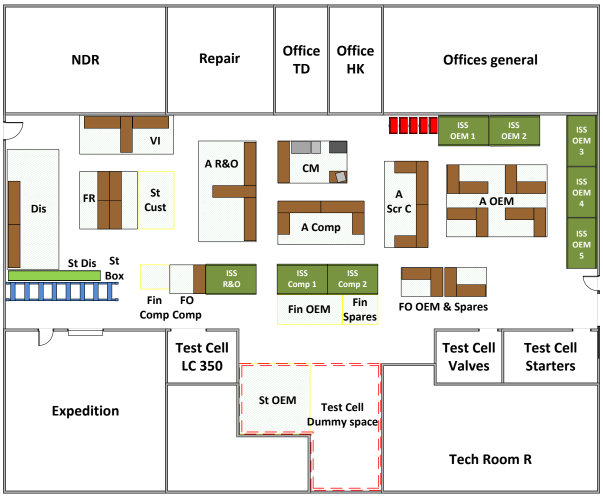
R&O cell concepts B and C, and OEM concepts A, B and E are the remaining cell concepts. These were merged together to form six complete layout alternatives. Although this might not have been apparent earlier, the cell concepts were designed conjunctively with interaction with the other cell firmly in mind. Consequently, joining them together did not require any adjustments, as the reader can see in the representations below. To guarantee the separation of used and new parts, a visual separating line on the floor between A R&O and A Comp running down until the ISS, is deemed sufficient. Used parts are then never to cross that line from the R&O assembly area to the OEM assembly areas. The six layout alternatives are depicted in smaller figures, but the reader can refer back to the relevant cell concepts for more detail. The layout before redesign is also shown again and scored in Chapter six to illustrate the benefits of the new layout alternatives over the current layout.



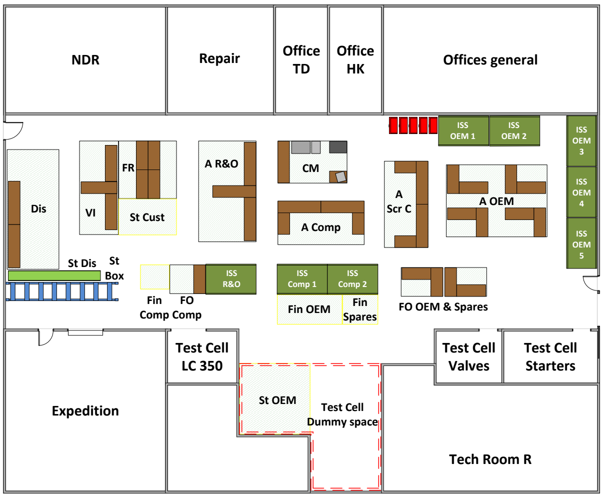
Layout alternative 1 (R&O B + OEM A)



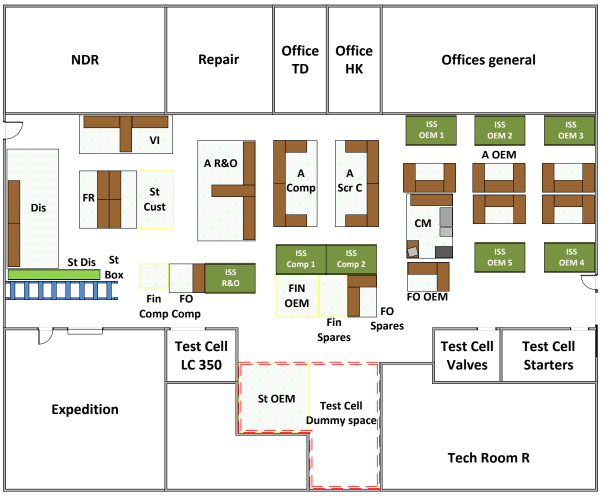
Layout alternative 2 (R&O C + OEM A)



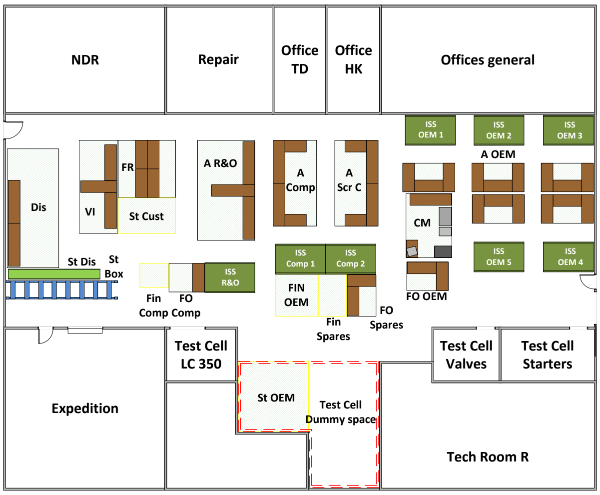
Layout alternative 3 (R&O B + OEM B)



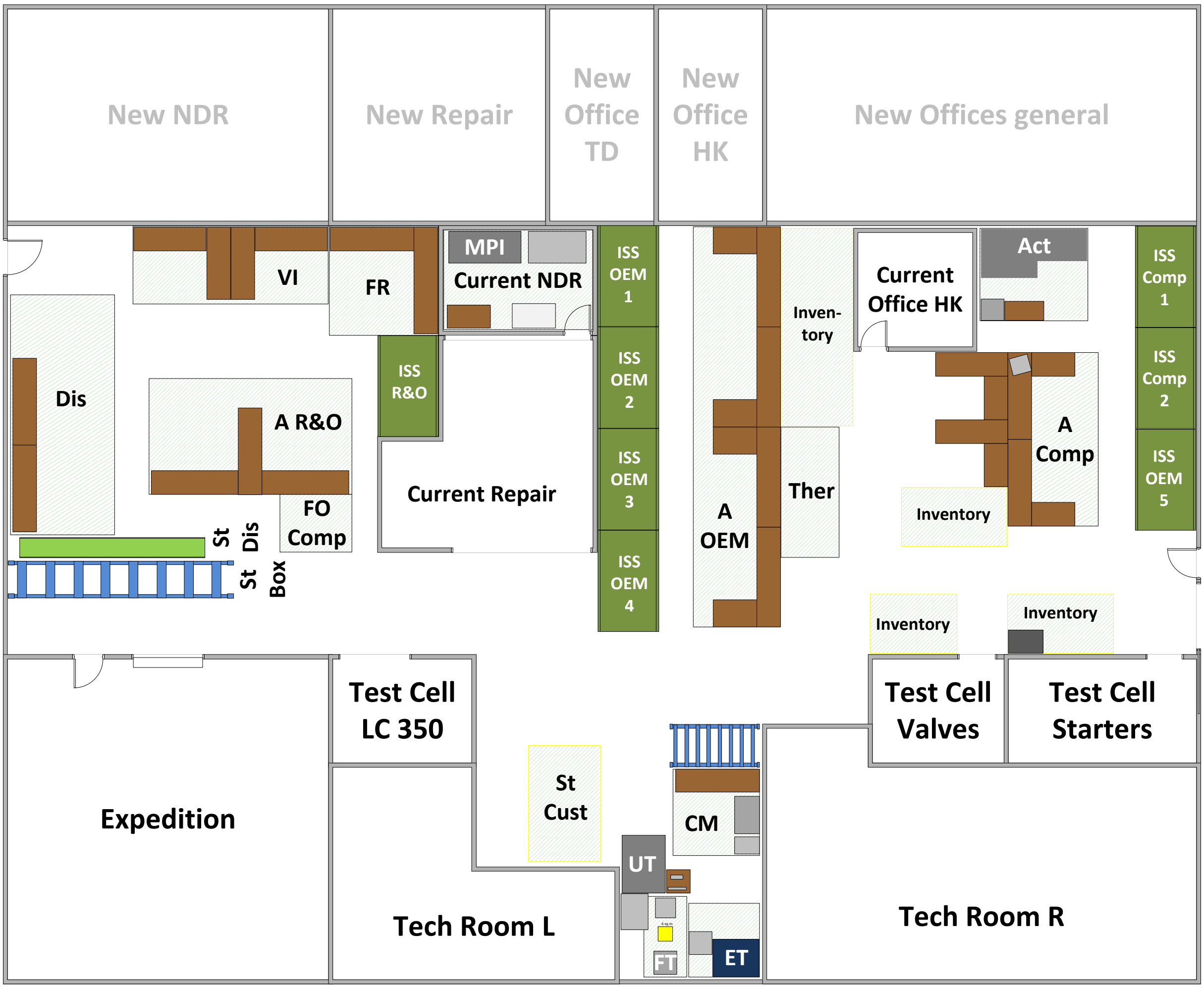
Layout alternative 4 (R&O C + OEM B)



Layout alternative 5 (R&O B + OEM C)



Layout alternative 6 (R&O C + OEM C)



Layout before redesign

6 Evaluation of layout alternatives

Chapter six deals with decision making. The scores on all eleven performance criteria are first presented for the current layout and the six layout alternatives, after which the scoring is explained with an example. The decision making hierarchy for the Analytic Hierarchy Process (AHP) is developed next, followed by the multi criteria scores resulting from AHP. A sensitivity analysis is performed before deciding on the best layout solution.

6.1 Layout alternative scores

Table 6 below shows the layout alternatives' scores on the eleven performance criteria. The criteria are repeated beneath the scores to refresh the memory. The scores do not yet provide a relative judgement of the layouts' performances. AHP will be used for this purpose. First however, the scoring is explained for all performance criteria by using Layout alternative one as an example. The scoring example starts on the next page.

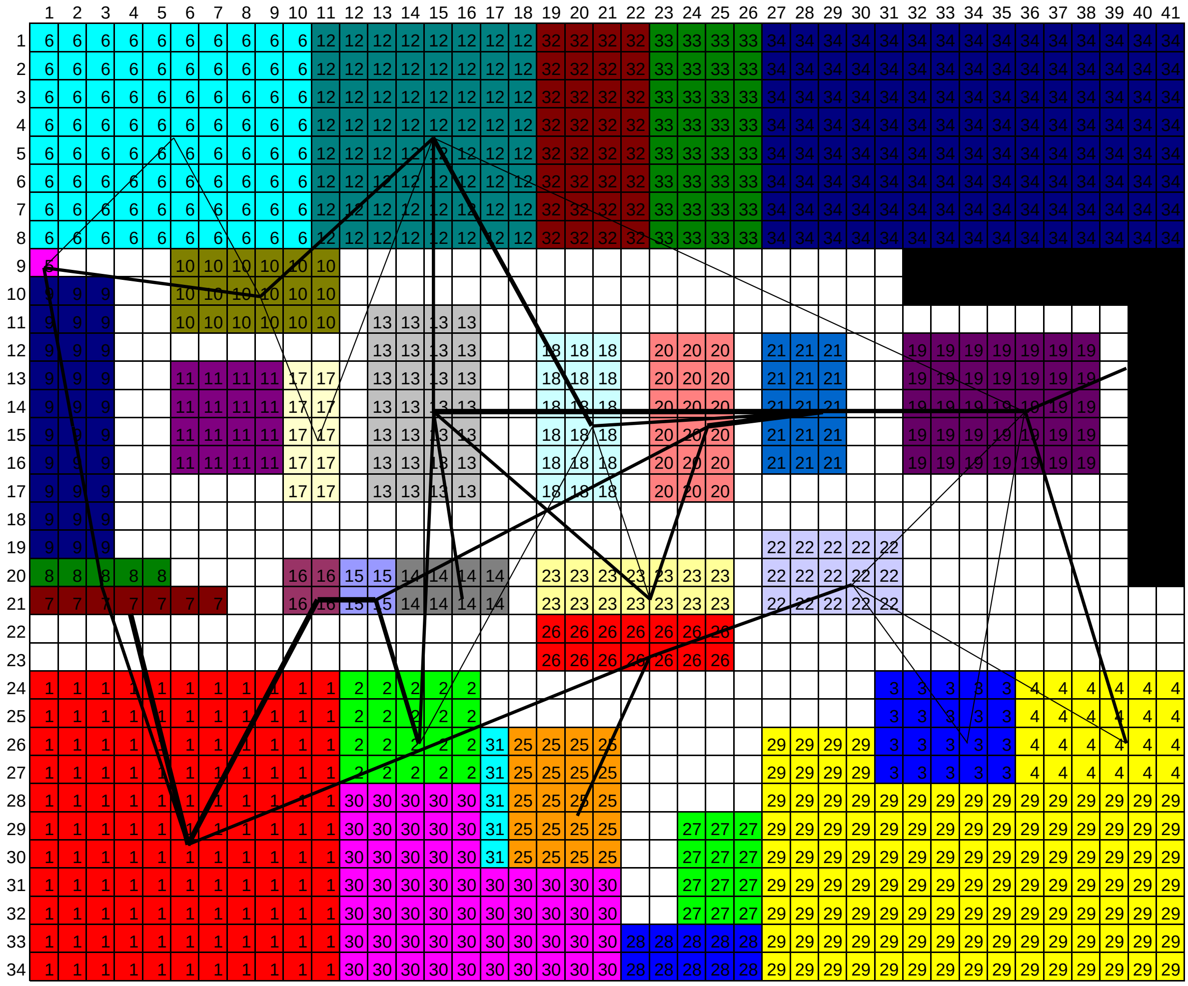
Layouts Criteria	**Before redesign**	**Alt. 1**	**Alt. 2**	**Alt. 3**	**Alt. 4**	**Alt. 5**	**Alt. 6**
1	10170	6856	6856	6967	7034	6883	6950
2	3247	1810	1753	1650	1643	1918	1911
3	OEM – R&O R&O – TC LC	TC LC – All assembly stations	TC LC – All assembly stations	TC LC – All assembly stations	TC LC – All assembly stations	All TC – All assembly stations	All TC – All assembly stations
4	35	108	111	124	127	116	119
5	0.6	0.87	0.87	0.87	0.87	0.87	0.87
6	-	R&O: 6.5 x 1.2m A Comp: 3.0 x 1.0m A Scr C: 3.0 x 1.0m A OEM: 7.0 x 2.1m	A Comp: 3.0 x 1.0m A Scr C: 3.0 x 1.0m A OEM: 7.0 x 2.1m	R&O: 6.5 x 1.2m A OEM: 3.0 x 2.1m CM: 1.2 x 2.9m	A OEM: 3.0 x 2.1m CM: 1.2 x 2.9m	R&O: 6.5 x 1.2m	-
7	1	8	8	8	8	7	7
8	€ 0,-	€ 71 724,-	€ 71 724,-	€ 71 724,-	€ 71 724,-	€ 79 524,-	€ 79 524,-
9	0.48	0.54	0.61	0.56	0.60	0.51	0.55
10	3	9	9	9	9	9	9
11	0.8	1	1	1	1	1	1

Theoretical Criteria		Operationalised Criteria
1. Minimal length of flow	→	1. Sum total weighted distance travelled (m)
2. Minimal backtracking & crossovers of flow	→	2. Sum weighted travel distance in contrary directions (m)
3. Minimal separation of departments by physical boundaries	→	3. Separation by physical boundaries (qual.)
4. High proximity of departments requiring informal communication	→	4. Sum of achieved desirability of adjacency (qual.)
5. High visibility of WIP	→	5. Ratio of WIP stages physically visible
6. Ease of future expansion	→	6. Total space for workstation scalability (m^2)
7. High flexibility of layout	→	7. Fixed elements in facility (qual.)
8. Low required investment	→	8. Cost of alternative solutions (€)
9. Effective movement of personnel	→	9. Average ratio shortest side / longest side of workstations
10. High employee comfort (lighting, noise, ventilation)	→	10. Freedom from noise by Repair section (qual.)
11. Ability to meet demand requirements	→	11. Ratio of space requirements for workstations fulfilled

Table 6: Layout scores on criteria

1. *Sum of total weighted distance travelled.*

The first criterion was evaluated with the aid of the CRAFT algorithm, developed by Jensen (2011). Entering the layout into CRAFT resulted in an approximate model of the layout with all required elements, which is shown in Figure 15. CRAFT calculated the rectilinear distances of flow between elements by using the flow data in the from-to chart of Appendix G and the coordinates in the model. flow weights equal to one were assigned to all flows, because batches are counted as one flow, and the cost of moving each flow is similar. An added bonus was that CRAFT visualises the flow with a simplified spaghetti diagram. The black lines thus represent flows. Flow going from the R&O cell to the OEM cell can be observed, e.g. between A R&O (dept. 13 in the figure) and CM (21). No used parts will end up in new products however, because these flows are complete Load Compressors e.g., being moved for an operation on the balancing bench. The score is 6856 weighted meters travelled.



Department	Color	Department	Color	Department	Color	Department	Color
Exp	1	VI	10	A OEM	19	Ther	28
TC LC	2	FR	11	A Scr C	20	Tech R	29
TC AFV	3	R	12	CM	21	Tech L	30
TC S	4	A R&O	13	FO OEM	22	Dum TC	31
Dum Cl	5	ISS R&O	14	ISS Comp	23	Office TD	32
NDR	6	FO Comp	15	ISS OEM		Office HK	33
St Box	7	Fin Comp	16	St OEM	25	Offices	34
St Dis	8	St Cust	17	Fin OEM	26		
Dis	9	A Comp	18	Act	27		

Figure 15: CRAFT model of Layout alternative one; Source: (Jensen, 2011)

2. Sum weighted travel distance in contrary directions

To calculate the score for this second criterion, the CRAFT model was slightly modified. The general direction of flow was first determined, and any flow moving in a contrary direction was highlighted in the from-to chart. All other flows were set equal to nil in the chart. The result was that CRAFT now only evaluated the highlighted flows, i.e. those moving in a contrary direction to the general flow. The result was the desired value, and in Layout one's case this distance was 1810 meters.

3. Separation by physical boundaries

This qualitative criterion is best judged with the drawing of Layout one. Elements in the drawing which could act as physical boundaries to informal communication are inventory racks and Inventory Storage Systems. The blue St Box separates Expedition from the R&O area. However, there is already a wall and door there, so this is separated anyway. The ISS R&O and two ISS Comp do cause for some separation by themselves. The TC LC is separated from all Assembly areas and thus we note 'TC LC – All assembly stations' as the score for Layout one.

4. Sum of achieved desirability of adjacency

To calculate the score on the criterion 'high proximity of departments for informal communication', the REL chart in Figure 13 is slightly modified. The difference is that the desirability ratings for adjacency are first quantified by exchanging the letter ratings for numbers (A=64, E=16, I=4, O=1, U=0, and X=-1024). The numerical values show progressively larger differences to make ratings of A, E and X weigh more heavily, and are typical weights used in Seehof & Evans' ALDEP algorithm (1967). The resulting numerical REL chart is shown in Figure 16. Recall that only departments with people manning them are represented in the REL chart.

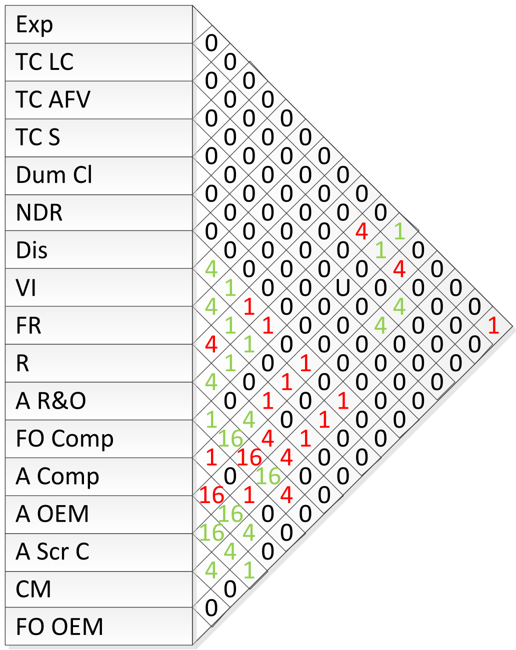


Figure 16: numerical REL chart Layout one

With the aid of the layout drawings, the achieved adjacencies were determined. For Layout one e.g., A Comp and A OEM are not positioned adjacent to each other, so that relationship is marked in red. A OEM and A Scr C are positioned adjacent to each other so this relationship is green. Setting all the red marked relationships equal to nil, and then taking the sum of all green ratings gives the total score for this criterion. In the case of Layout one, its score is 108.

5. Ratio of WIP stages physically visible

A WIP stage was said to be visible when the WIP is in a unique physical location corresponding to one particular stage of the process, and can be seen in that location. If one and the same location is used for two WIP stages, or is retracted from sight, then it is not deemed a visible WIP stage. Recall that to achieve higher visibility of WIP, the new elements FO OEM, Fin OEM and Fin Comp were devised.

Now to the score. Several WIP stages were defined (For R&O: Waiting for disassembly, In Disassembly, In Cleaning, In Visual Inspection, In Findings Report, Waiting for customer approval, In Repair, In Assembly R&O, In Testing LC, In FO, Waiting for shipment; and for OEM: In Assembly, In Testing, In FO, Waiting for shipment.) For layout one, Cleaning and Repair are retracted from sight by the walls between them and the rest of the APF, so these are regarded as not visible. All other thirteen stages are visible WIP stages. One could argue that the ISS R&O and ISS Comp block the visibility of the TC LC and thus WIP stage 'In Testing LC'. However, this is not the case because this test cell is visible from most of the R&O cell's area, just not from the assembly areas. For that reason, it is still counted as visible. The ratio score for Layout one is 0.87. The same score is achieved by all other layouts. This is unsurprising since it is the new elements which determine the difference between the layout before redesign and the new alternatives. All new designs have these elements, hence the similar scores. Keep this in mind when reading the scoring of criterion number seven, fixed elements in facility, because that criterion results in varying scores, proving it is different from this criterion.

6. Total space for workstation scalability

Space for scalability at workstations was measured with the aid of Microsoft Visio. Room to scale up a workstation is only available when this can be done without violating a constraint or using other stations' space. In the APF's case, aisle space of 1.20 m wide had to be reserved because pallet carts travel along them. Figure 17 shows how space for scalability was measured. The space in the green rectangle can be used for expansion at R&O for either FR and St Cust, or for VI by first moving FR and St Cust down, and then increasing the space at VI. Layout one performed best on this criterion with scalable expansion possible in the R&O cell and at the elements A Comp, A Scr C and A OEM.

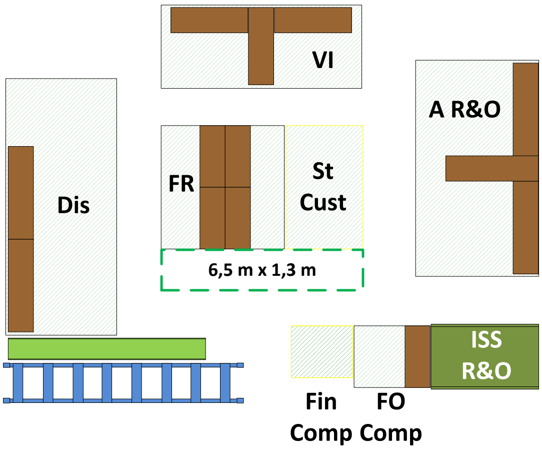


Figure 17: Example of scalability space R&O

7. Fixed elements in facility

Looking again at the drawing, one sees that the ISS R&O and the two ISS Comp are not placed at an edge of the APF, so these possibly inhibit flexible rearrangement of elements. The other ISS are positioned along the walls of the APF and the St Box and St Dis are also at the edge of the R&O section. The criterion is a qualitative one so it is scored on a scale of one to ten, with layout one receiving an eight. Two, three and four receive the same mark, with five and six receiving a seven for the two ISS placed in the A OEM area. The layout before redesign is hardly flexible so it gets a three.

8. Cost of alternative solutions

A rudimentary cost overview is given in Table 7. Activities to refurbish the APF and small amounts of new equipment are necessary, but not overly expensive. The moving of the big ISS and other heavy equipment is expensive, because specialised companies have to be hired at high cost. The biggest cost comes from lost production time. One week of lost production time in total is expected for the entire R&O and OEM departments at an hourly budgeted cost of €90,46 (Elting, 2012).

Layout alternative 1	**Units**	**Unit cost**	**Hours**	**Hourly cost**	**Total**
APF refurbishment					
Deconstruct walls in APF	-	-	48	€ 60,-	€ 2.880,-
Install air extraction at Repair section	1	€ 2.000,-	0	€ 0,-	€ 2.000,-
Apply new wiring	1	€ 1.500,-	32	€ 60,-	€ 3.420,-
Apply floor markings	1	€ 500,-	24	€ 80,-	€ 2.420,-
Reinstall lighting	-	-	16	€ 60,-	€ 960,-
Relocation of elements					
Relocate ISS	5	€ 3.000,-	0	€ 0,-	€ 15.000,-
Relocate heavy equipment	7	-	4	€ 120,-	€ 3.360,-
New equipment					
Tool trolleys	5	€ 300,-	0	€ 0,-	€ 1.500,-
PC's	5	€ 300,-	0	€ 0,-	€ 1.500,-
Workbenches	10	€ 250,-	0	€ 0,-	€ 2.500,-
Production time					
Lost production time	-	-	400	€ 90,46	€ 36.184,-
Total cost					**€ 71 724,-**

Table 7: Investment cost for Layout alternative 1

9. Average ratio shortest side / longest side of workstations

Figure 18 explains how the ratios for the effective movement of personnel were calculated. Normally the shortest- and longest side of a rectangle encompassing an element is measured. In the case that two elements are 'stuck together' like in this figure, they are joined into one rectangle. Employees will obviously have to walk around them as though they are one. This particular workstation in the figure has a ratio of 3.9 / 6.5 = 0.65. Layout one's average ratio is 0.54, making it a mediocre performer.

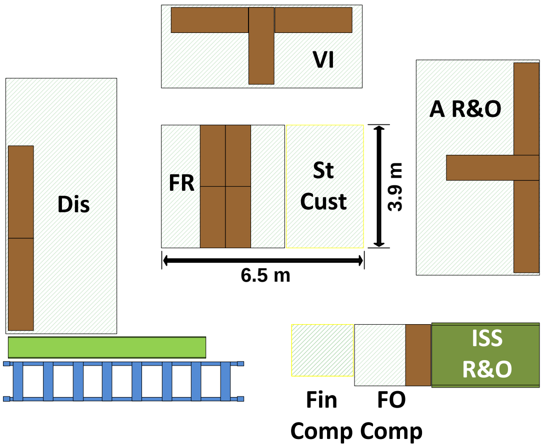


Figure 18: Example of shortest/longest side

10. Freedom from noise by Repair section

This criterion is judged qualitatively as well. With the Repair section housed in a separate room, noise from the Repair section will hardly be a problem. All new layout alternatives therefore score a nine. Because Repair is in the middle of the APF in the current layout, that receives a three.

11. Ratio of space fulfillments for workstations fulfilled

The final criterion shows if the required capacity is met. It was possible to comply to all space requirements for the new layout, so all new layouts can meet the expected required capacity for the coming years. Their ratio's are therefore all one.

6.2 Choosing the best layout with the Analytic Hierarchy Process

Recall from Saaty, R. (1987) that the first key principle of the Analytic Hierarchy Process is to structure the decision problem into a hierarchy of goal, criteria and alternatives. The seven layout alternatives are at the bottom of the hierarchy and are evaluated with the eleven performance criteria, which make up the second level. Another level up, the performance criteria are grouped into branches of criteria, those branches being workflow criteria, employee related criteria and production capacity criteria. E.g. one sees that all criteria corresponding to the flow of work are grouped under the workflow criteria branch. At the highest level of the hierarchy, the overall goal of the decision making problem is to select the best layout for Aeronamic. The complete decision hierarchy is shown in Figure 19 on the next page.

The second principle is to make pairwise comparisons to determine relative weights in the hierarchy. To determine the relative performance of each layout alternative on a performance criterion, the designer made pairwise comparisons based on the scores from Table 6. Aeronamic's management was asked to participate in a session to determine the relative importance of the criteria within a branch and the relative importance of the branches themselves, by making pairwise comparisons of their own. That way, their preferences were considered formally in the decision making process. For those that are interested, the derivation of weights from the pairwise comparisons is an elaborate mathematical procedure which is explained in Appendix H. Here, only the final scores for all layout alternatives are presented. They can be found in Table 8, also on the next page.

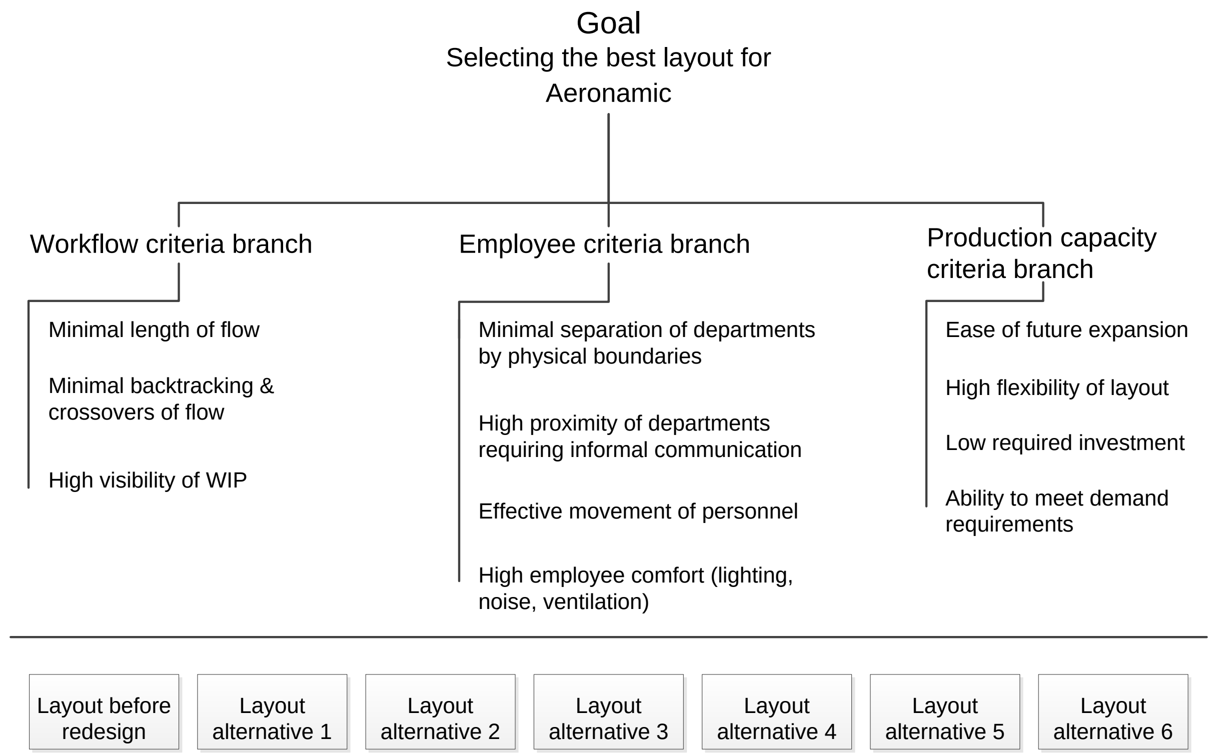


Figure 19: Decision making hierarchy APF problem

Alternative	Bef Red	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6
Relative priority	0.0345	0.1820	0.1760	0.1775	0.1739	0.1317	0.1244

Table 8: AHP Relative priorities layout alternatives

Unfortunately the relative priorities from AHP are inconclusive. The layout before redesign scores poorly as could be expected, but although layout alternatives five and six perform less than the others, alternatives one, two, three and four could all be chosen as the final solution. What these results do indicate, is that the flexible assembly stations outperform the dedicated OEM assembly stations in this multi criteria analysis. The differences in the final score between alternatives one, two, three and four are more subtle, but in Table 6 one could see they do vary in performance on various criteria. The conclusion is then that the weights assigned to the criteria might prevent a winner from surfacing.

To explore that possibility, sensitivity analysis was applied to the branches of criteria. The original branch weights were 0.4 for workflow, 0.4 for employee and 0.2 for production capacity. The weight of one branch was then set to vary between nil and one, with the other two branches changing along so that the relation between them did not change. The following three graphs resulted from the analysis.

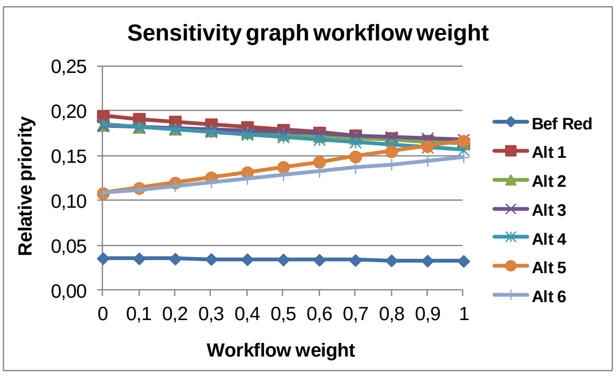


Figure 20: Sensitivity analysis workflow branch

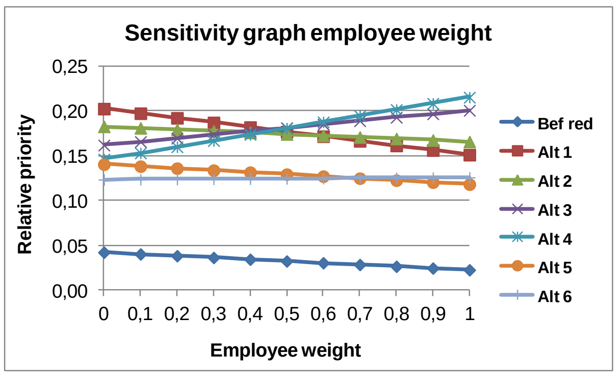


Figure 21: Sensitivity analysis employee weight

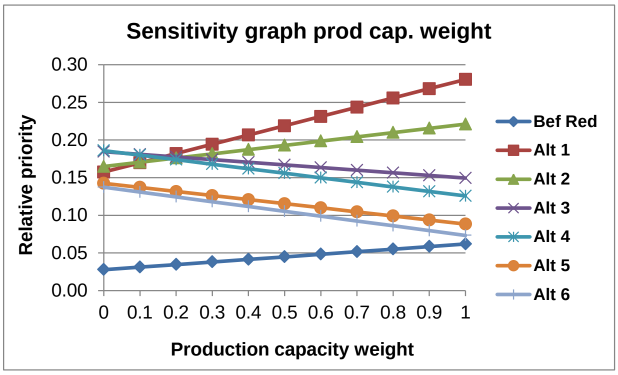


Figure 22: Sensitivity analysis prod cap. weight

One can see in Figure 20 that when the workflow criteria branch is made more important, all final scores converge. This is logical because the alternatives score most similar on these criteria. When looking at Figure 21, the picture is slightly different. If the employee criteria are deemed more important, alternatives three and four pull away from one and two. In Figure 22 the opposite is observed. Especially alternative one is the clear favourite when the criteria grouped under production capacity are the most important.

During the sessions in which management performed the pairwise comparisons of the criteria and branches, the workflow and employee branches were designated as the criteria a company makes money on. The criteria in the production capacity branch are prerequisites to operate, but do not directly affect profits. For this reason, the first two criteria branches were given more weight by management in the first place. Extrapolating this thought leads to a preference for layout alternatives three and four. Management should keep in mind though, that a choice for alternative one provides Aeronamic with the most flexible and expandable layout which will mean that layout can be expected to meet the company's needs for the longest period of time.

Which one to choose then? Hyer, Brown and Zimmerman's Social Technical Systems approach advocates great employee involvement for best results. Since the formal decision making tool does not give a clear indication which alternative is best, the operator's preferences and willingness to work with a solution will go a long way to determine which layout alternative eventually fits best.

After the inconclusive initial scores and the sensitivity analysis, layout alternatives one, three and four were shown to the operators one final time for them to make a choice. They unanimously chose alternative one. All operators truly did not want a walking aisle along the northern edge of the R&O cell, thus eliminating alternative four. They chose alternative one over alternative three because of its calmer appearance.

6.3 Conclusion Chapter six: the final layout solution

Layout alternative one has been selected as the future layout for the Aerospace Production Facility, chosen partially with the aid of AHP and ultimately chosen by the operators who will be working with the layout for the coming years. The key characteristics of this layout that make it different from the layout before the redesign are that it employs flexible assembly stations at Assembly OEM, has new workstations like the Common Machine section and Final Out stations, finds the NDR and Repair sections in the expansion and has all Inventory Storage Systems placed along the edges of the facility. The layout is detailed and presented along with further recommendations in the next chapter.

7 Recommendations

The recommended layout for the APF, with all required elements and details, is given as a scaled drawing in Figure 23 on the next page. It has an R&O and OEM cell, the former with a product layout, the latter with a functional layout and new flexible assembly stations. The Repair and NDR sections have been moved from the R&O cell to the expansion and new elements (A Scr C, Common Machine, Final Out and Finished Goods) have been added. Last but not least, all Inventory Storage Systems have been placed along the edges or walls of the facility to increase openness. Next, the detailing of the layout for Aeronamic's Aerospace Production Facility (APF) is discussed. Thereafter, further recommendations for successful implementation and successful use of the layout are given.

7.1 Detailing of layout

NDR and Repair

During conceptual design, the new NDR and Repair 'cells' in the expansion were not yet designed in detail. In conjunction with the Social Technical Systems approach, these cells were designed predominantly by the operators themselves. To improve the openness of the entire APF, the walls separating NDR and Repair from the rest of the APF shall be made of see through acrylic glass. These walls are coloured sky blue in the drawing. Minor adjustments were made to the NDR design with the same openness in mind. The Actuator Testing installation (Act) was initially placed along the bottom wall of the NDR cell. The Act is high, and would thus block the view into NDR from the R&O cell. Therefore it was exchanged with Eddy Current Testing (ET), which is significantly lower in height.

5S

Lean tool 5S was to be used as a design principle. Desired is thus a layout where everything has a designated place, from where it can be easily retrieved. Everything that is not required, must be stored away. Tools are one of the most important resources to the operators. These are to be stored in shadow boards so that every operator can see if something is missing. These shadow boards are represented by the blue elements on the workbenches. The tool trolleys for Assembly OEM (A OEM) are also shadow boards for the same reason, but because they are mobile they require space for storage and for use. When in use, they should go in the dashed red blocks in the A OEM area. When not in use, they can be stored where the reader sees them in the drawing, left of ISS OEM 1.

Recall that material handling is done with trolleys, which are also in use or not. Storage space is thus provided for when they are vacant, so that all employees know they are available for use. The yellow areas under Findings Report (FR) and Common Machining (CM) represent that space.

Visual Process Controls

Visual Process Controls are the preferred method of communication. First, notice the dashed red line indicating used parts must not cross over from the R&O cell to OEM. Second, workflow between workstations can be visually controlled by employing 'Kanban' trolley blocks. The reader can observe these as dashed yellow blocks in both the R&O and OEM cell. Taking a part of the R&O cell as an example, there are Kanban blocks at Disassembly (Dis), above the Disassembly workbench and at Visual Inspection (VI). When VI has free blocks at its workstation, it takes a trolley with work from one of the right two blocks above Dis, which are its input blocks. They are not coincidentally also the output blocks for the Cleaning process, so Cleaning sees one of their outputs was taken. Cleaning then takes a trolley with work from one of its input blocks to the left of its output blocks, which is Disassembly's output block. Disassembly can then take an R&O job out of the Storage for Disassembly (St Dis) to begin the process for that job. This is applied to all R&O process steps. One deviation is that the Test Cell LC 350 has three input blocks, located beneath Storage Customer (St Cust). This is because LC 350's also come from Assembly Compressors (A Comp). Final Out Compressors (FO Comp) has only one input block at its station because that step takes significantly less time to complete and will thus always be ready for work. The Finished Product spaces are the input Kanban blocks for Expedition.

Furthermore, to communicate information on WIP statuses, production schedules and performance, one video screen was used as the Visual Process Control in the layout before redesign. However, this was only visible to the R&O operators. Because the operators should work as one team, they should also all get the same information. To this purpose, a large projector screen with all relevant information located in the center of the APF should be installed. The screen can be fit high on the two ISS Comp so that everyone can see it from every angle.

Lighting

The last requirement to be considered is sufficient lighting at all workstations. Lights hanging from the ceiling are to be installed, with extra lighting at the Visual Inspection station. Because the expansion takes away the windows in the top wall of the APF, the amount of daylight is reduced significantly. Because daylight is desirable, it is recommended to install light domes in the ceiling as well.

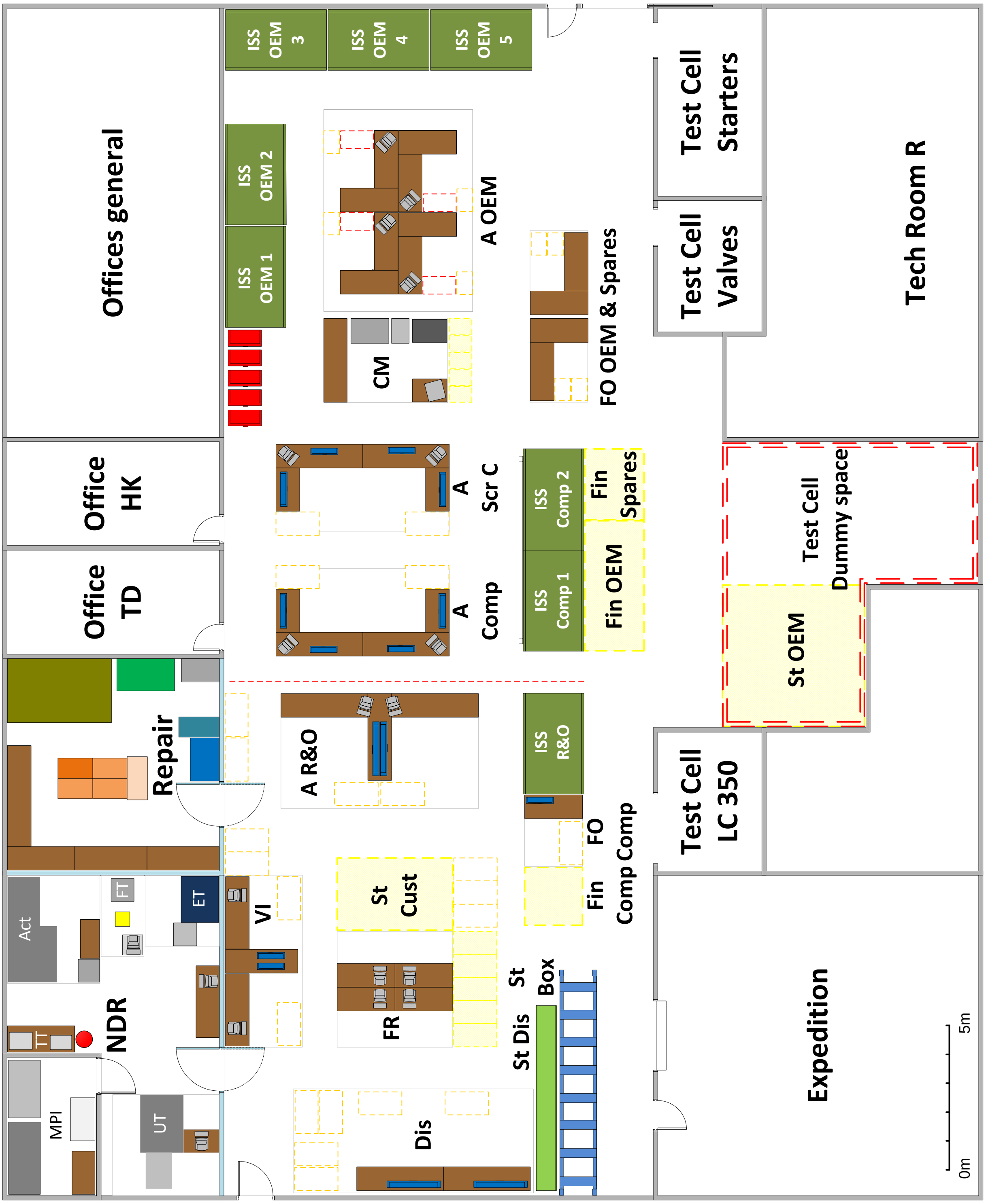


Figure 23: Recommended detailed layout for the Aerospace Production Facility

Flow

To illustrate how the products produced in the APF will flow through the facility in the recommended layout, a second drawing of the layout with the general flow paths is given in Figure 24. Not every flow is visible in this drawing, only the big flows. The detailing is also taken out again for clarity of the drawing. Finally, the drawing does not take movements into and out of KANBAN blocks into account for the same reason.

The reader can observe three colours of arrows, which represent the flows of three product groups. The orange flows are Load Compressors in Repair & Overhaul, which start and finish at Expedition and move along a single row path. The red flows are new compressor products, starting at the ISS Compressors and moving towards Final Out Compressor to join the other Load Compressors. Then, the blue arrows are the other OEM products, which originate at the ISS OEM and finish at Finished goods OEM before moving to Expedition as well. It is easy to see that the flow is progressive from its origin to the destination and not extremely messy either.

The dashed arrows leading to and from the Common Machine (CM) section are the flows corresponding to the movement of product assemblies going to either the balancing bench, measurement table or oven. To be excessively clear on this, they are not used parts.

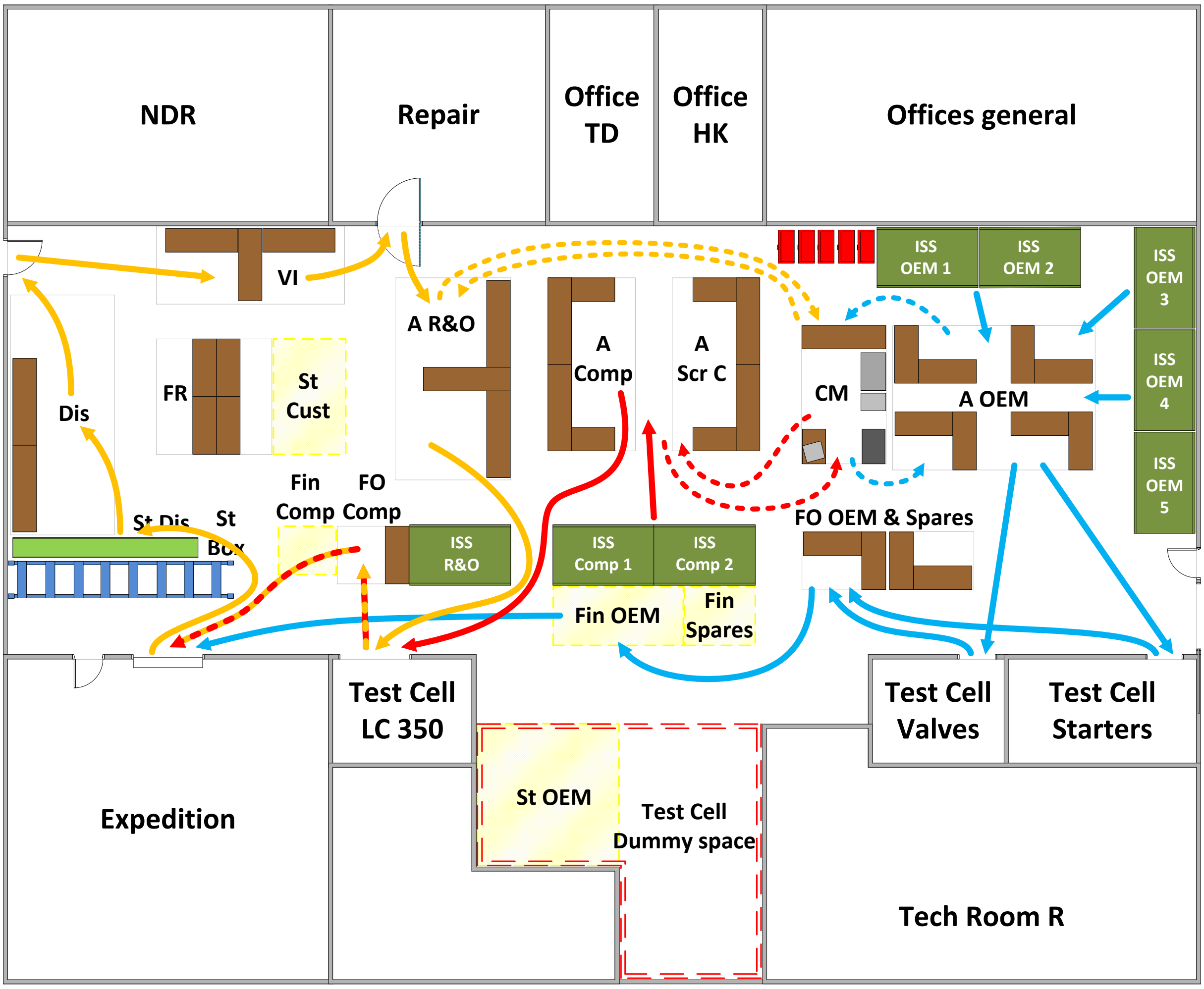


Figure 24: Recommended layout with general flow path directions

7.2 Further recommendations on implementation and use

Implementation

Important for implementation is that the Repair and NDR sections and the Actuator Testing Installation are fixed in the current layout. If their functioning is required, these cannot be moved until the expansion is ready. Unfortunately, Repair and NDR are in the center of the APF, so rearrangement of the entire layout is impossible before the expansion is ready. Very small parts of the layout could already be changed but the greatest benefits will not be enjoyed right until that wall of Inventory Storage Systems (ISS) in the middle is replaced. Therefore it is not sensible to make a substantial effort to rearrange only small parts of the layout.

Another point of attention concerning implementation of the layout are the ISS. Not only do some of them need to be relocated, many also require different contents to function in their new roles. This will be a time consuming process and must be done carefully to make parts picking as efficient as possible. Because of their importance, changing to the flexible assembly stations is only possible once the contents of the ISS have been rearranged completely. The following implementation steps result.

1. Build the expansion
2. Move Repair, the NDR elements and Office Han Kleisen to their new areas
3. Deconstruct current Repair, NDR and Office HK
4. Rearrange ISS and workstations
5. Reallocate inventory to new ISS
6. Implement tool trolleys to change to flexible assembly stations

Successful use

As the reader can see in Figure 23, the storage space for packaging materials (St OEM) is placed in the area reserved for the new test cell. This was done because there actually was no space for it anywhere else. To prevent that inventory dispersing itself over the APF like it has done in the current layout, that space should be kept. This can be done by placing St OEM on top of the test cell after it is built. This is possible because all the packaging materials are light in weight.

Other reserved space, that for the assembly of Scroll Compressors, can be used for other purposes until the time the Scroll Compressor actually enters production. Aeronamic should be careful not to place anything there that requires space that is not available when this happens.

Employee involvement was an important element of this research. However, involvement should not stop after the completion of this layout redesign project. Being truly Lean includes employees that are actively involved in continuous improvement, both of the layout and other elements in the production process. In the current situation, Aeronamic's employees are insufficiently encouraged to analyse and improve them. Doing this more will result in more benefits from the employed Lean techniques like 5S.

To be able to participate in continuous improvement, Hyer, Brown and Zimmerman (1999) outlined in their Social Technical Systems approach that employees need to be given training and responsibility. Letting R&O and OEM operators take basic Lean training courses, and providing them with the responsibility and time to think about improvements are thus important aspects of becoming Lean.

Another important training factor is increasing the operators' skill sets. According to Pagell (2004) people should be diversely trained so they can rotate between many different jobs. Actually rotating people among all jobs will also increase the feeling of being one team, responsible for the entire APF.

It should be crystal clear by now that the layout design is not the only determinant for the achievement of the goals set for it. Both Pagell and Hyer e.a. said that social structures should support the layout goals. Increased flexibility, i.e. working as one team, cannot be achieved as long as social structures do not support this. E.g. performance evaluation and rewarding should be done on a team basis instead of an individual basis if team thinking is desired. In any case, it is important that every (future) decision affecting the APF be (re)considered for their effect on workflow and workforce flexibility.

8 Scientific relevance of this research

This applied research has employed a combination of many elements from literature on criteria, layout design procedures, layout design tools and solutions. A multi criteria perspective on the problem was elected whilst the design process was undertaken with a combination of the Systematic Layout Planning (SLP) and Social Technical Systems (STS) approach. CRAFT was chosen as the design tool to aid in the design and evaluation process after which a combination of AHP and employee preferences determined the choice for the eventual layout. Two elements deserve special mentioning.

Scientific literature has long since embraced the multiplicity of criteria involved in a layout problem, and rightly so. Formally developing multiple criteria not only ensures the alternative solutions are evaluated properly, but improves the design's quality. Looking at the similarity in the six layout alternative's scores on some criteria, it seems that a designer implicitly accounts for the criteria in the designs. Doing so improves the quality of the designs. A research on how the development of criteria impacts a layout design process could be conducted to verify this assumption.

The SLP approach is a necessary element of layout design because the technical requirements have to be accounted for. By applying STS, operators were involved throughout the entire design process, from the development of criteria up to the detailing of the final design, with very interesting effects. For one, initial resistance to an idea like the flexible assembly stations turned into enthusiasm once the benefits were clear to them. The greatest benefit of STS was however, that actively involving the operators also delivered new ideas which the designer had not thought of. The outcome of this research; a widely accepted solution with visible improvements on the criteria, therefore supports STS's claims that it improves solution quality and employee acceptance.

Finding the desired scientific theories and selecting the appropriate elements from the literature was a cumbersome affair, not least due to the sheer magnitude of literature available on the subject. A second difficulty was that science models very specific situations of the layout problem. This renders most of the theory inapplicable to the practical situation covered in this research. It is here where most of the scientific community's attention should be directed towards.

First of all, every layout problem has its own characteristics, goals and difficulties. Experience from this project shows that no layout design procedure or design tool is perfectly suitable for the practical layout problem a designer is trying to solve. Developing ever more advanced procedures or computer algorithms for each specific situation is probably impossible, nor will it solve the problem. Increased supply simply means it will become harder to find what you need.

The author of this report spent close to 40% of his time on reading and selecting literature on layout design. In any business environment, no layout designer will have anywhere near that time. The result is that many layouts are designed on gut feeling instead of with appropriate procedures and tools. Many researchers, Cambron & Evans (1991) and Francis, McGinnis Jr. & White (1991) e.g., bemoan this outcome and argue that results are so much better when the products from scientific research are used to aid layout designers. However, that is not addressing the problem.

A perfectly suitable design procedure, with perfect design tools does not exist for practical problems and they are not at all necessary either. Layout design is a social and technical matter where a solution should satisfice those involved. A selection of methods and tools which are known to offer better solutions than just designing on intuition, and are accessible to everyone would mean that on the whole, layout designers would be able produce better quality layout solutions. The suggestion is thus for science to perform a special type of comparative study.

It would be extremely interesting to see a comparative study on the performance of layout design procedures and design tools, not on a specific situation like was performed in Appendix E of this report or in the researches by Kusiak & Heragu (1987) and Cambron & Evans (1991), but on a wide range of problems. One would hope to find a number of design procedures and tools that offer reasonable solutions for different situations. It is this robustness of their solutions that is far more interesting than their ability to optimally solve one specific layout problem. The most robust procedures and tools can subsequently be presented as suitable for practical use.

One possible method to do this is the use of stochastic input variables. Making them probabilistic gives a researcher the possibility to determine the probability that a layout design procedure offers a decent solution. Naturally, a research of this kind would require a lot of time and resources because many layout designers will have to use the procedures and tools on many different layout problems. The human factor in the generation of results will also influence the results, but the possible outcome justifies the effort in the author's opinion.

If the proposed study is successful, a second requirement for layout designers to actually use the robust design procedures and tools is the development of user friendly design packages. Commercial layout design software hardly exists. The few software packages that were found, are based on the Systematic Layout Procedure, which only uses the qualitative REL chart to determine a layout. Because the software was not actually used during this research, the remainder of the argument is based on assumptions. If a layout designer wishes to employ other performance measures and easily apply multiple criteria then he/she requires more software. In the best case, several different software packages will be used. In the worst case, layout designers must develop their own algorithms and multi criteria models. Assuming most designers will either not be able or not inclined to do this, an easy commercial 'plug and play' package is required.

9 Conclusion

To arrive at a satisfactory new layout for improving workflow and the flexible deployment of the Aerospace Production Facility's workforce, eleven performance criteria were developed using scientific literature and operator input. Fourteen constraints also applied to Aeronamic's layout problem. These can all be found in Table 1 on page 17.

Application of known literature on plant layout to Aeronamic's situation resulted in a conceptual layout consisting of two cells. A Repair and Overhaul cell with a product layout was shown to be most applicable to the production process in that cell, whereas the Original Equipment Manufacturing cell's processes proved most compatible with a functional layout.

The design process involved intense operator involvement because of the chosen Social Technical Systems approach, and also included the use of a CRAFT algorithm to optimise flow. Six layout alternatives resulted, which were scored on the eleven criteria. The best alternative was subsequently sought through outranking with the Analytic Hierarchy Process. The operator's preferences finally tipped the balance towards the detailed layout found in Figure 23 on page 47.

Key changes to the layout are that the Repair and NDR sections have been moved from the R&O cell to the expansion, the OEM cell has flexible assembly stations at the Assembly OEM workstation, new elements (Assembly Scroll Compressor, Common Machine, Final Out and Finished Goods) have been added and all Inventory Storage Systems have been placed along the edges or walls of the facility.

Recommendations for the implementation of the new layout were given, along with recommendations on other important success factors for the achievement of the layout redesign's goals. Finally, a brief discussion on the merits of the multi criteria approach to layout design and the Social Technical Systems approach was followed by an argument to focus research effort more on finding robust layout design procedures and tools, which are more easily applicable to a wide range of layout problems.

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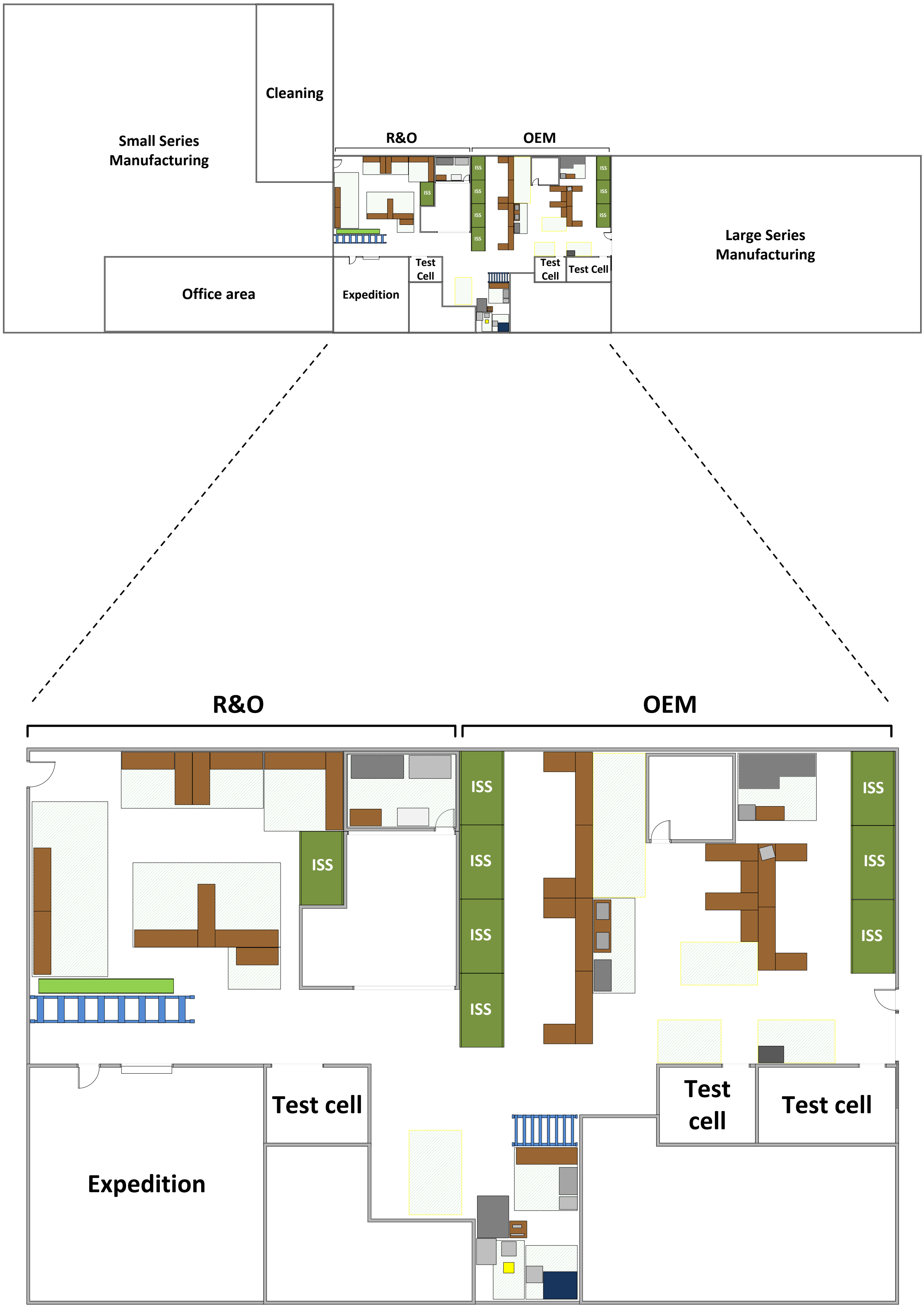
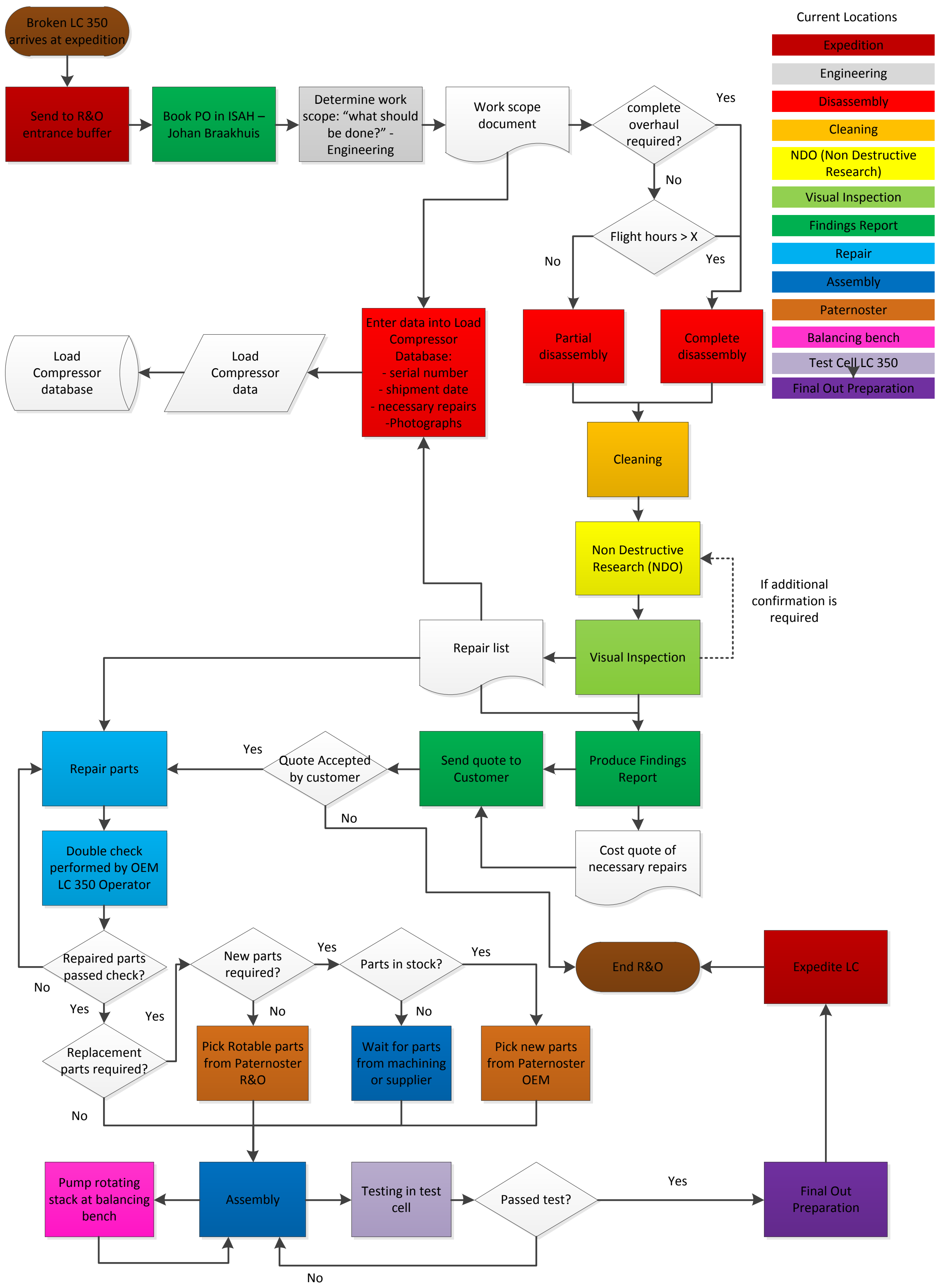
Appendices

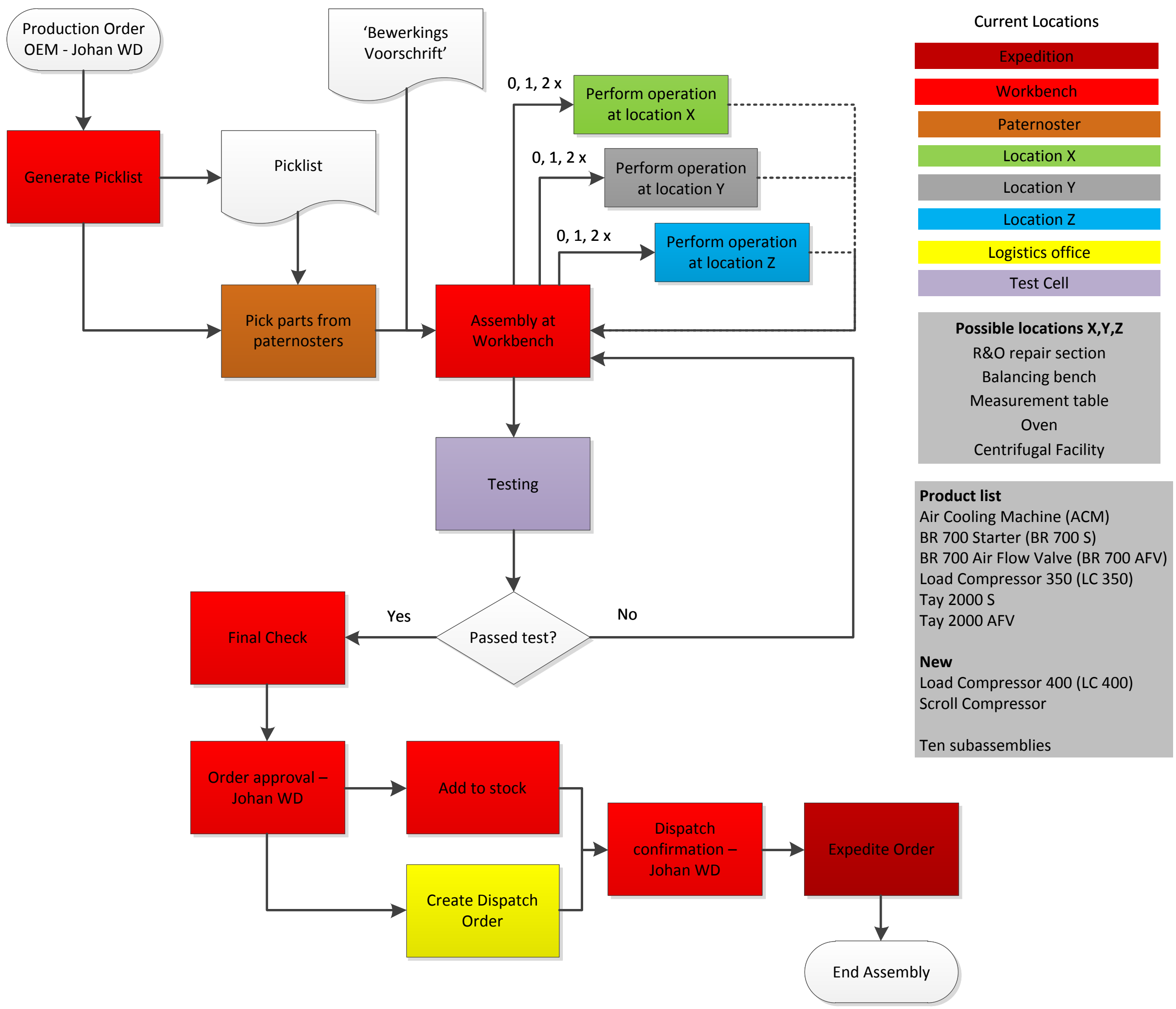
Appendix A: Current layout plan Aeronamic



Appendix B: Process Flow Chart R&O



Appendix C: Process Flow Chart OEM



Appendix D: Worked calculation examples 'volume ratio'

These worked examples for calculating the volume ratio as presented in Section 3.1 correspond to the OEM demand for the Load Compressor 350. Data is from Aeronamic's Enterprise Resource Planning system ISAH.

For all OEM products, the volume of production is planned in advance. This means variability in demand can be foreseen and anticipated upon. The OEM monthly demand for the LC 350 from November 2004 till April 2012 is depicted in Figure 25 below.

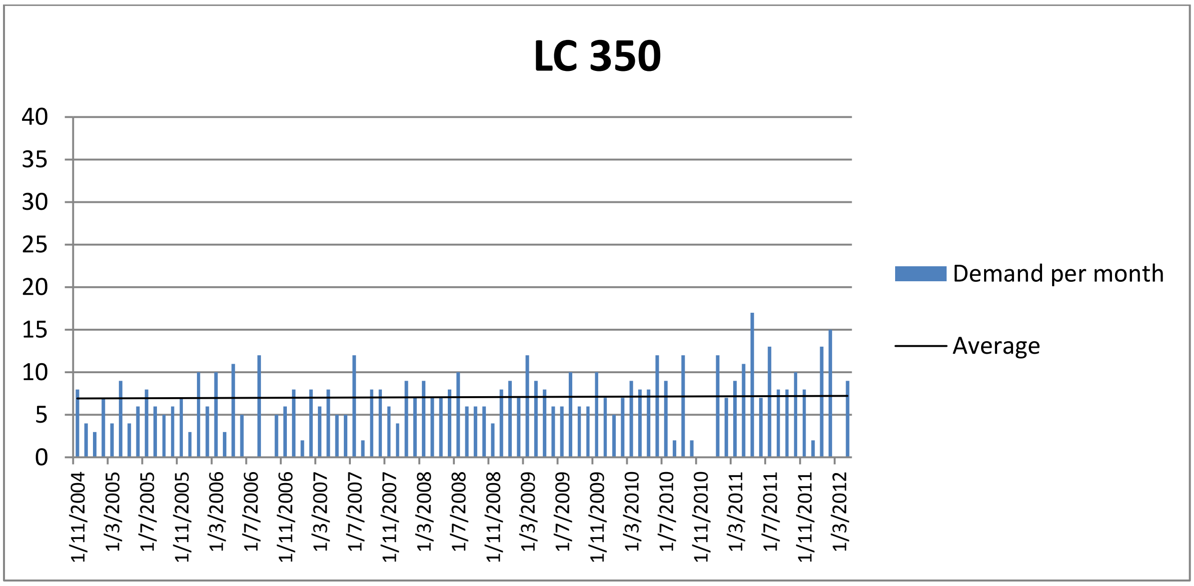


Figure 25: LC 350 expected demand per month; Source: (ISAH, ERP Production Orders, 2012)

Operator ratio
An average monthly demand of seven is observed, and because demand is not expected to change this is also the expected demand in Table 2. The cycle time for every product was derived from the product route lists (ISAH, ERP Product Route List, 2012). For the LC 350, this is 15.6 hours per product. This number was verified by the operators to be accurate. One more number is required for the ratio; the monthly production time per operator/FTE.

It is assumed that 85% of an operator's time can be used productively. The rest of the time is used for training, meetings and other activities. There are 52 weeks in a year, of which five are for paid leave. Then, with a working week of 40 hours, the monthly operator time for one FTE is = 0.85 * 47 * 40 / 12 = 133 hours per month.

The operator volume ratio for the LC 350 is then $\frac{7 * 15.6}{133}$ = 0.82

Workbench ratio
In the OEM assembly area, the workbench is a resource that is always available, unlike the operator. It can be 100% utilised meaning that the monthly workbench time equals 52 * 40 * 12 = 173 hours per month. The assumption in this calculation is that all operators work at the same time, where it is known that flexible hours from seven 'o clock in the morning till six 'o clock in the afternoon exist. If this were also taken into account, the total production time per workbench would be even greater.

The workbench volume ratio for the LC 350 is then $\frac{7 * 15.6}{173}$ = 0.64

Appendix E: Review of Computer Aided Design algorithms

Introduction to computer algorithms
For the development of a solution algorithm, the formulation of the problem is instrumental. The most common quantitative formulations are those of the discrete *Quadratic Assignment Problem* (QAP) and the continuous *Mixed Integer Programming Problem* (MIP). Their aim is to minimise material handling cost. QAP handles the problem by assigning facilities to discrete grids or boxes in a rectangle. Departments can occupy several boxes if needed. MIP aims to place all facilities in a planar shape, where they may not overlap. Both use from-to chart data to calculate weighted travel distances between departments.

The benchmark QAP algorithm is without a doubt CRAFT (Computerised Relative allocation of Facilities Technique) as developed by Armour & Buffa (1963). This algorithm uses pairwise exchange of adjacent departments to improve an initial layout. An initial solution thus has to be provided by the user. CRAFT calculates the weighted rectilinear distance travelled by materials from one department centroid to another department's centroid and sums these values for all departments to obtain the total layout score. If an exchange of two adjacent departments offers an improvement, e.g. exchanging department one and two from Figure 26 (which is a repetition of Figure 10), the exchange is made. If no such exchange exists, the algorithm terminates. Because CRAFT improves existing layouts it is known as an improvement type algorithm. Other QAP formulations for minimal space costs, minimal rearrangement costs and minimal backtracking also exist, but they are few in number and apply only to specific situations like single-row layouts.

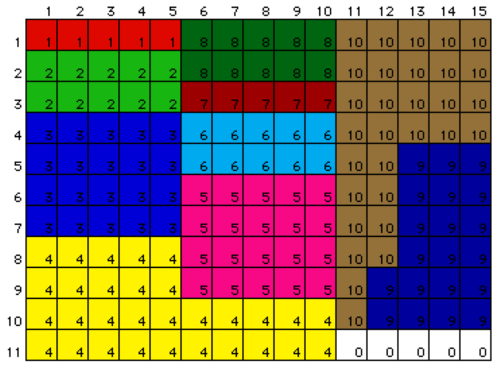


Figure 26: Example of CRAFT

Qualitative approaches generally work with the Relationship (REL) chart presented in Section 2.2 as developed by Muther (1973). Their aim is maximise desired adjacency of departments. CORELAP (Computerized Relationship Layout Planning) as developed by Lee & Moore (1967) and ALDEP (Automated Layout Design Program) as developed by Seehof & Evans (1967) were the benchmark algorithms for this approach until the 1990's.

"CORELAP constructs a layout for a facility by calculating the total closeness rating (TCR) for each department, where the TCR is the sum of the numerical values assigned to the closeness ratings in the REL chart between a department and all other departments" (Lee & Moore, 1967). The department with the highest TCR is placed first in the layout. Subsequently, departments with the highest closeness rating (A) are placed adjacently to the existing department. If there is no department with A, then the REL chart is scanned for departments with closeness rating E and so on. If there is a tie between departments at this point, the department with the highest TCR is placed first. CORELAP continues with this process until all departments have been assigned.

ALDEP is different from CORELAP in that it attempts to produce multiple layouts for the user to choose between, whereas CORELAP aims for one best layout. ALDEP chooses the first department to include randomly. From then onwards, it uses the same selection procedure of highest closeness rating first to assign the other departments. It produces multiple solutions because it performs its construction with many different first choice departments. Assigning the departments is done with a sweeping procedure which is illustrated in Figure 27. The first department is assigned to the top left of the facility. The following departments are added along the sweep pattern. The width of the sweep is for the user to play around with until acceptable solutions are obtained. The figure shows three departments as they were assigned with sweep widths of two and four.

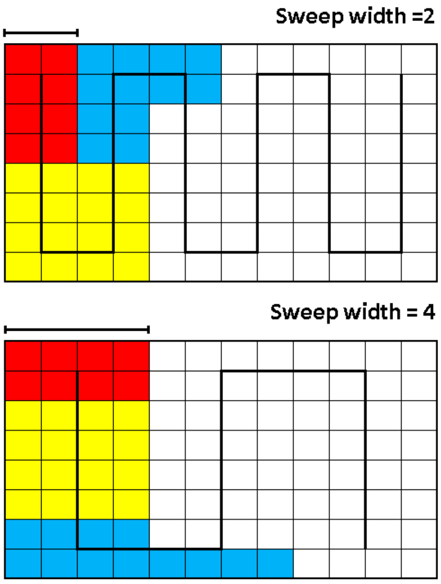


Figure 27: Sweep width ALDEP

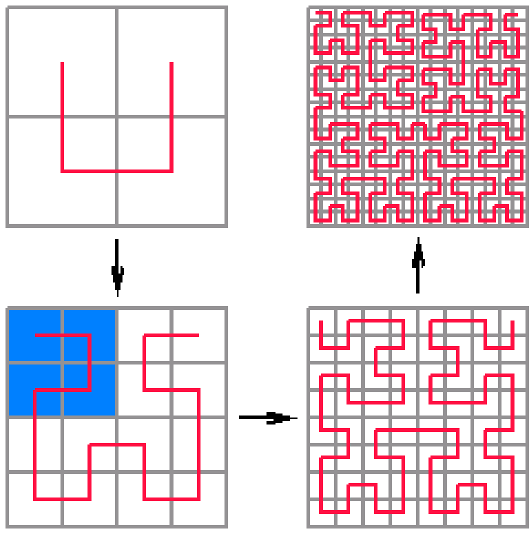


Figure 28: Space filling curves

Two notable other algorithms are MULTIPLE and LOGIC. MULTIPLE is an improvement type algorithm that improves an initial solution through pairwise exchange of departments. The difference with CRAFT is that it uses space filling curves (SPC) to assign departments. These curves are vectors of varying complexity that run through the entire facility, as depicted in Figure 28. Assigning departments happens along the SPC. E.g. for assigning a department with a space requirement of four tiles to the bottom left facility, the SPC would be followed starting from the top left corner, and the department would be assigned to the four tiles the SPC traverses first, which are the blue shaded tiles.

LOGIC cuts a facility into partitions to which departments are assigned. Imagine a facility being cut first into two partitions along the vertical axis. LOGIC then assigns one set of departments west of the cutline and one set of departments east of the cutline in such a manner, that material handling cost among these sets and between the two sets is minimised. It keeps cutting until all departments have been assigned to their own partition. Because it always starts with a complete facility, LOGIC is of the construction type.

Neither the quantitative nor the qualitative approach was believed to suffice on its own because of the presence of multiple criteria in a practical situation. Multi goal- and multi criteria models were developed as a result. Most authors used a linear combination of objectives to obtain more comprehensive objective functions, or combined the criteria into one by using the Analytic Hierarchy Process (AHP) for decision making at the end. Houshyar (1991) found that layouts were still generated with the aid of algorithms though. For completeness, uncertainty about the accuracy of data has led to the development of models based on fuzzy logic.

To conclude the presentation of algorithms, two more recent developments are the use of simulated annealing (SA) and genetic algorithms (GA). They are mostly presented as improvement algorithms. SA is unique in its ability to accept non improving solutions in an algorithm. It does this to enable the algorithm to explore other solutions. The problem of getting stuck in a local optimum is thus avoided. GAs employ ‘genetics’ because they create new generations of solutions from high performing existing solutions. SA and GAs use many different algorithms in their procedure so they are difficult to classify.

Strengths and weaknesses

The main algorithms previously introduced and their characteristics are located in Table 9. The last three columns contain new information that will be treated in the forthcoming discussion. Because multi criteria models, Simulated Annealing and Genetic Algorithms borrow from other algorithms it is not useful to include them in this table.

Solution approach	*Disc. / Cont.*	*Type*	*Objective*	*Shapes*	*Fixed elements*	*User dependence*
CRAFT	Discrete	Improvement	Min. dist.	Any	Strong	High
CORELAP	Discrete	Construction	Max. adjac.	Any	Weak	High
ALDEP	Discrete	Construction	Max. adjac.	Any	Medium	Medium
LOGIC	Continuous	Construction	Min dist.	Rectangles	Weak	Low
MULTIPLE	Discrete	Improvement	Min dist.	Any	Strong	High
MIP	Continuous	Construction	Min dist.	Rectangles	Strong	Low

Table 9: Solution methods for generating layout alternatives

Discrete models are not able to represent the exact positions of departments, nor can they model specific constraints like pick-up and drop-off locations, or orientations of departments. Continuous models are able to do this, meaning they will approach practical solutions more closely. However, continuous models do require more processing power and CPU time.

Construction type algorithms start with a blank layout and generate one best solution. Advantages are short computation times and that this type is unbiased. With only one objective, obtaining one best solution is great, but with multiple criteria to satisfy there might be a need for more alternatives. Only ALDEP provides multiple solutions. Improvement types have as a weakness that they are dependent on the initial layout given as input and are thus biased. This does enable them to offer multiple solutions easily in a direction the layout planner is thinking, but at higher computational effort.

Considering the two major objectives of solution algorithms, minimizing the distance travelled is quantitative and measurable. It is also based on objective input, being the flow of materials between departments / workstations. Maximizing adjacency requires the determination of desirability of closeness between departments by the user, making the method biased and dependent on human judgement. It does offer the possibility of considering more criteria in the closeness ratings.

Some algorithms are able to work with non rectangular shapes, which increases the freedom in design and enables odd shapes for certain machines or workstations. Only allowing rectangles limits the solution space. An algorithm that is able to deal with fixed elements is more useful in a practical situation because restrictions may be present like walls, columns or fixed department locations.

User dependence can be positive and negative. Dependence at the start can be good when a layout designer wants to be able to see an algorithm's outcome from his/her layout ideas, but this also takes time. This applies to CRAFT and MULTIPLE which require initial layouts to work. Dependence on the user at the end is negative, because if a designer has to make frequent adjustments to outcomes, it implies the algorithm poorly represents the realistic situation.

SA is more advanced than regular improvement algorithms. It accepts non optimal solutions temporarily, which reduces dependence on the user to provide good initial input. GAs are popular in contemporary literature, but they are very demanding in terms of CPU time.

Algorithms have also been compared by researchers on their results to layout problems. Kusiak & Heragu (1987) draw no conclusions on what is the best algorithm as it depends on the specific problem how they perform. Cambron & Evans (1991) also concluded more research was needed to decide on which algorithm performs best in certain conditions. From the discussion above, it should come as no surprise that there is no best performing algorithm or approach. It depends on the circumstances of the layout problem, the objective and the constraints.

Appendix F: Choosing the computer algorithm for layout generation

To fully comprehend the choices made in this section, the reader is advised to have read Appendix E.

First, recall two of this research's prime objectives, minimal flow length and minimal crossovers and backtracking of flow to improve clarity of flow. Translating them to an objective function, minimizing backtracking does not necessarily reduce the length, but minimizing distance travelled does improve the clarity of flow as backtracking and crossing over affect length. Maximizing desired adjacency as the objective has the benefit of considering multiple criteria, but could still result in very long flow lengths. Because an algorithm usually works with a single objective, minimizing distance travelled is the preferred algorithm objective, which rules out CORELAP and ALDEP.

Length of flow however, is just one of many criteria. A choice must be made whether to incorporate them all into an algorithm's objective function or to judge solutions after generation. Out of the nine operationalised criteria, five are quantitative and four are qualitative. In Section 2.2 it was decided that quantifying these four criteria requires excessive calculations or that they are simply better judged by people. These qualitative criteria thus exclude the possibility of having a complete multi goal algorithm objective, because they need to be judged by the layout designer and not by the algorithm. The quantitative criteria could still be used together by an algorithm, but the nature of the criteria prevent this. The ratio shortest/longest side of a block e.g., is something only LOGIC and MIP would be able to handle properly, as all other algorithms have assignment methods with non-rectangular shapes. Also, the total reserved space for scalability of departments / workstations and the investment costs are design decisions which an algorithm cannot make nor evaluate. A multi criteria analysis will therefore have to be performed after generation of alternatives and one objective will be used in the algorithm.

The requirements and constraints in Table 1 also affect the choice for an algorithm. There are fixed locations for certain departments and area must be reserved for aisle space and inventory storage, so dealing with fixed elements is important. Also, designing along a Social Technical Systems approach means there is a strong need for employee involvement in the design process because of their knowledge and for commitment reasons. This indicates improvement type algorithms are more suitable than construction types, because they enable working with ideas by turning them into initial layouts. Management also has ideas about the best layout. Being able to show multiple alternatives with their respective scores on the criteria will provide insight in the design process. An algorithm that produces more solutions is thus preferable.

Time constraints in the project dictate general solutions must be found quickly, so using an algorithm that is simple to implement is key. The design process is largely a human affair and after finding the layouts of departments, note that sufficient time is still required for scoring, choosing and detailing. Simulated Annealing and Genetic Algorithms are inherently more difficult and will take too much time to develop for this layout problem. The algorithms that tick the most proverbial boxes in this discussion are CRAFT and MULTIPLE. CRAFT is simpler, but MULTIPLE's solutions are generally better because it is less dependent on the user's initial input. Since trying different ideas is desired however, and the algorithm has a more evaluative function than true generation of layouts, this does not weigh heavily. The simplest option is therefore preferred and a CRAFT algorithm will thus be used to evaluate and improve layout alternatives generated by human design.

Appendix G: From-to chart for functional elements in the APF

The from-to chart below gives the monthly flow of materials from row elements to column elements.

From / To	Exp	TC LC	TC AFV	TC S	Dum CI	NDR	St Box	St Dis	Dis	VI	FR	R	A R&O	ISS R&O	FO Comp	Fin Comp	St Cust	A Comp	A OEM	Scr C	CM	FO OEM	ISS Comp	ISS OEM	St OEM	Fin OEM
	Fixed						**R&O**											**OEM**								
Fixed																										
Exp	0	0	0	0	0	0	25	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TC LC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	34	0	0	0	0	0	0	0	0	0	0	0
TC AFV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	6	0	0	0	0
TC S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	9	0	0	0	0
Dum CI	0	0	0	0	0	0,33	0	0	0	24,7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NDR	0	0	0	0	0	0	0	0	0	0,33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R&O																										
St Box	25	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
St Dis	0	0	0	0	0	0	0	0	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dis	0	0	0	0	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VI	0	0	0	0	0	0	0	0	0	0	0	20	0	0	0	0	5	0	0	0	0	0	0	0	0	0
FR	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	0
R	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	22	2	0	0	0	0	0	0	0
A R&O	0	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	0
ISS R&O	0	0	0	0	0	0	0	0	0	0	0	0	23	0	0	0	0	0	0	0	0	0	0	0	0	0
FO Comp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	59	0	0	0	0	0	0	0	0	0	0
Fin Comp	59	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
St Cust	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OEM																										
A Comp	0	9	0	0	0	0	0	0	0	0	0	22	0	0	0	0	0	0	0	0	14	0	0	0	0	0
A OEM	0	0	9	12	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	17	3	0	0	0	0
A Scr C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	0	25	0	0	0	0	0
CM	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	14	17	25	0	0	0	0	0	0
FO OEM	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	18
ISS Comp	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	9	0	25	0	0	0	0	0	0
ISS OEM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21	0	0	0	0	0	0	0
St OEM	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	18
Fin OEM	18	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

Source: (ISAH, ERP Production Orders, 2012), (Vries de, Production volume cross check, 2012)

Appendix H: AHP calculations example

The axiomatic foundations for the Analytic Hierarchy Process outlined in this appendix, can be found in the article by its developer, Saaty T.L. (1986). AHP starts with making pairwise comparisons between elements in the same levels of the decision making hierarchy. They are entered into a matrix, which is used to calculate the relative weights. Those weights are then used to arrive at the final relative priorities found in Table 8. To illustrate the process, the employee criteria branch is used as an example. All other pairwise comparison matrices and resulting relative weights are given at the end of this appendix section.

The employee criteria branch consists of four criteria. These are entered into a 4x4 matrix, shown in Table 10. Management was asked to make pairwise comparisons of the criteria to determine which they considered to be more important. For this purpose, they assigned the ratings explained below.

A matrix entry a_{ij} means that the ROW element is

1 = equally
3 = weakly
5 = strongly
7 = very strongly
9 = absolutely

more important than the COLUMN element. (2,4,6 and 8 are intermediate numbers)

Employee branch	Sep. Phys.	Prox. Dept.	Eff. Move.	Emp. Com.
Separation by physical boundaries	1	2	4	6
Proximity of departments	1/2	1	3	4
Effective movement of personnel	1/4	1/3	1	3
Employee comfort	1/6	1/4	1/3	1

Table 10: Pairwise comparison matrix employee criteria branch

Looking at the table, by putting a 4 in the entry Sep. Phys. – Eff. Move., management says they find separation by physical departments between weakly and strongly more important than effective movement of personnel. Note that the matrix is reciprocal. That means that the entry Eff. Move. – Sep. Phys. is ¼ by definition. Were this not the case, then great inconsistency could arise.

One of AHP's strengths is that it actually does allow for some inconsistency in judgement, but too much inconsistency is undesirable. To measure the decision maker's consistency, Saaty developed the Consistency Ratio (CR). Required to calculate this ratio are the principal or largest eigenvalue λ_{max} of the matrix, and the Random Consistency Index (RI) found in Table 11 for the corresponding matrix order n. If the CR < 0.1 then the matrix is said to be sufficiently consistent. If the CR exceeds 0.1, the decision maker has to revise the matrix entries. The following formulas compute the CR.

CR = $\frac{CI}{CR}$ with

CI = $\frac{\lambda\,\text{max} - n}{n-1}$ in which n is the order of the matrix

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 11: Random Consistency Index

The principal eigenvalue λ_{max} for the employee matrix was found to be 4.0875 using MATLAB®. The Consistency Index (CI) is then calculated by entering λ_{max} and n = 4 into the formula for CI.

CI = $\frac{4.0875 - 4}{4-1}$ = 0.029

CR = $\frac{0.029}{0.90}$ = 0.032 < 0.1 so the matrix is consistent.

The next step is to calculate the relative weights for the criteria in the employee branch. For this purpose, the 4x4 matrix is risen to subsequently higher powers, with the normalised eigenvector for each matrix giving weights of the criteria. When the weights stop changing after a next iteration, one assumes that the weights correctly represent the decision maker’s preferences. The five iterations for the employee branch matrix are given in Table 12. The reader can observe that the weights do not change significantly anymore from the third iteration onwards. After five iterations, the weights are almost entirely unchanging, and thus assumed stable.

	Weights matrix^1	Weights matrix^2	Weights matrix^3	Weights matrix^4	Weights matrix^5
Sep. Phys.	0.4761	0.4983	0.4993	0.4986	0,4986
Prox. Dept.	0.3054	0.3028	0.2986	0.2988	0,2989
Eff. Move.	0.1647	0.1348	0.1361	0.1367	0,1367
Emp. Com.	0.0629	0.0641	0.0659	0.0659	0,0659

Table 12: Weights from normalised eigenvector for five powers of matrix

Calculation of relative priorities layout alternatives

Exactly the same process is performed at all levels in the hierarchy. After having found all the weights, the relative priority for a layout alternative in the employee branch is found with the following formula:

$$\text{Relative priority}_{\text{employee}} = \text{Score}_{\text{Sep. Phys.}} * \text{Weight}_{\text{Sep. Phys.}} + \text{Score}_{\text{Prox. Dep.}} * \text{Weight}_{\text{Prox. Dep.}} + \text{Score}_{\text{Eff. Move.}} * \text{Weight}_{\text{Eff. Move.}} + \text{Score}_{\text{Emp. Com.}} * \text{Weight}_{\text{Emp. Com.}}$$

After having done the same for the workflow and production capacity branches, the total relative priority of a layout alternative is calculated as follows:

$$\text{Relative priority}_{\text{total}} = \text{Score}_{\text{workflow}} * \text{Weight}_{\text{workflow}} + \text{Score}_{\text{employee}} * \text{Weight}_{\text{employee}} + \text{Score}_{\text{prod cap.}} * \text{Weight}_{\text{prod cap.}}$$

To make the AHP process and determination of weights reproducible, all pairwise comparison matrices and weights can be found in Appendix I on the next three pages.

Appendix I: Pairwise comparison matrices and corresponding weights

Branches and Workflow branch

Goal	Workflow	Employee	Prod Cap.	Weights
Workflow	1	1	2	0.4
Employee	1	1	2	0.4
Prod Cap.	1/2	1/2	1	0.2

Workflow	Len. Flow.	Backtrack.	Vis. WIP	Weights
Len. Flow	1	3	1/2	0.309
Backtrack.	1/3	1	1/5	0.1095
Vis. WIP	2	5	1	0.5816

Len. Flow	Bef Red	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Weights
Bef Red	1	1/8	1/8	1/7	1/6	1/8	1/7	0.0218
Alt 1	8	1	1	1 1/2	2	1	1 1/2	0.1986
Alt 2	8	1	1	1 1/2	2	1	1 1/2	0.1986
Alt 3	7	2/3	2/3	1	1 1/2	2/3	1	0.14
Alt 4	6	1/2	1/2	2/3	1	1/2	2/3	0.1022
Alt 5	8	1	1	1 1/2	2	1	1 1/2	0.1986
Alt 6	7	2/3	2/3	1	1 1/2	2/3	1	0.14

Backtrack.	Bef Red	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Weights
Bef Red	1	1/6	1/6	1/7	1/7	1/5	1/5	0.0244
Alt 1	6	1	1	1/3	1/3	1/2	1/2	0.0841
Alt 2	6	1	1	1/3	1/3	1/2	1/2	0.0841
Alt 3	7	3	3	1	1	4	4	0.2915
Alt 4	7	3	3	1	1	4	4	0.2915
Alt 5	5	2	2	1/4	1/4	1	1	0.1121
Alt 6	5	2	2	1/4	1/4	1	1	0.1121

Vis. WIP	Bef Red	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Weights
Bef Red	1	1/4	1/4	1/4	1/4	1/4	1/4	0.04
Alt 1	4	1	1	1	1	1	1	0.16
Alt 2	4	1	1	1	1	1	1	0.16
Alt 3	4	1	1	1	1	1	1	0.16
Alt 4	4	1	1	1	1	1	1	0.16
Alt 5	4	1	1	1	1	1	1	0.16
Alt 6	4	1	1	1	1	1	1	0.16

Employee branch

Employee	Sep. Phys.	Prox. Dept.	Eff. Move.	Emp. Com.	Weights
Sep. Phys.	1	2	4	6	0.4986
Prox. Dept.	1/2	1	3	4	0.2989
Eff. Move.	1/4	1/3	1	3	0.1367
Emp. Com.	1/6	1/4	1/3	1	0.0659

Sep. Phys.	Bef Red	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Weights
Bef Red	1	1/9	1/9	1/9	1/9	1/8	1/8	0.0185
Alt 1	9	1	1	1	1	2	2	0.1926
Alt 2	9	1	1	1	1	2	2	0.1926
Alt 3	9	1	1	1	1	2	2	0.1926
Alt 4	9	1	1	1	1	2	2	0.1926
Alt 5	8	1/2	1/2	1/2	1/2	1	1	0.1055
Alt 6	8	1/2	1/2	1/2	1/2	1	1	0.1055

Prox. Dept.	Bef Red	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Weights
Bef Red	1	1/5	1/5	1/7	1/7	1/6	1/6	0.0256
Alt 1	5	1	1	1/3	1/3	1/2	1/2	0.0869
Alt 2	5	1	1	1/3	1/3	1/2	1/2	0.0869
Alt 3	7	3	3	1	1	2	2	0.2527
Alt 4	7	3	3	1	1	2	2	0.2527
Alt 5	6	2	2	1/2	1/2	1	1	0.1476
Alt 6	6	2	2	1/2	1/2	1	1	0.1476

Eff. Move.	Bef Red	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Weights
Bef Red	1	1/5	1/6	1/5	1/6	1/4	1/5	0.0299
Alt 1	5	1	1/2	1	1/2	2	1	0.1353
Alt 2	6	2	1	2	1	3	2	0.2423
Alt 3	5	1	1/2	1	1/2	2	1	0.1353
Alt 4	6	2	1	2	1	3	2	0.2423
Alt 5	4	1/2	1/3	1/2	1/3	1	1/2	0.0797
Alt 6	5	1	1/2	1	1/2	2	1	0.1353

Emp. Com.	Bef Red	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Weights
Bef Red	1	1/6	1/6	1/6	1/6	1/6	1/6	0.027
Alt 1	6	1	1	1	1	1	1	0.1622
Alt 2	6	1	1	1	1	1	1	0.1622
Alt 3	6	1	1	1	1	1	1	0.1622
Alt 4	6	1	1	1	1	1	1	0.1622
Alt 5	6	1	1	1	1	1	1	0.1622
Alt 6	6	1	1	1	1	1	1	0.1622

Production capacity branch

Prod Cap.	Ease Exp.	High Flex.	Low Inv.	Abil. Dem.	Weights
Ease Exp.	1	3	7	3	0.5347
High Flex.	1/3	1	5	1	0.2175
Low Inv.	1/7	1/5	1	1/3	0.0597
Abil. Dem.	1/3	1	3	1	0.1881

Ease Exp.	Bef Red	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Weights
Bef Red	1	1/8	1/7	1/6	1/5	1/4	1	0.0279
Alt 1	8	1	2	4	5	6	8	0.3808
Alt 2	7	1/2	1	3	4	5	7	0.2698
Alt 3	6	1/4	1/3	1	2	3	4	0.1355
Alt 4	5	1/5	1/4	1/2	1	2	3	0.0912
Alt 5	4	1/6	1/5	1/3	1/2	1	2	0.0615
Alt 6	1	1/8	1/7	1/4	1/3	1/2	1	0.0332

High Flex.	Bef Red	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Weights
Bef Red	1	1/8	1/8	1/8	1/8	1/7	1/7	0.0208
Alt 1	8	1	1	1	1	2	2	0.1923
Alt 2	8	1	1	1	1	2	2	0.1923
Alt 3	8	1	1	1	1	2	2	0.1923
Alt 4	8	1	1	1	1	2	2	0.1923
Alt 5	7	1/2	1/2	1/2	1/2	1	1	0.105
Alt 6	7	1/2	1/2	1/2	1/2	1	1	0.105

Low Inv.	Bef Red	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Weights
Bef Red	1	7	7	7	7	8	8	0.5438
Alt 1	1/7	1	1	1	1	2	2	0.0896
Alt 2	1/7	1	1	1	1	2	2	0.0896
Alt 3	1/7	1	1	1	1	2	2	0.0896
Alt 4	1/7	1	1	1	1	2	2	0.0896
Alt 5	1/8	1/2	1/2	1/2	1/2	1	1	0.0489
Alt 6	1/8	1/2	1/2	1/2	1/2	1	1	0.0489

Abil. Dem.	Bef Red	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Weights
Bef Red	1	1/3	1/3	1/3	1/3	1/3	1/3	0.0526
Alt 1	3	1	1	1	1	1	1	0.1579
Alt 2	3	1	1	1	1	1	1	0.1579
Alt 3	3	1	1	1	1	1	1	0.1579
Alt 4	3	1	1	1	1	1	1	0.1579
Alt 5	3	1	1	1	1	1	1	0.1579
Alt 6	3	1	1	1	1	1	1	0.1579

Appendix J: Personal reflection

In this short reflection I will review my personal performance over the course of this research project. First I will present the personal learning objectives I aspired to achieve. Then I shall evaluate my performance on these objectives, after which I will also briefly evaluate the process of performing this bachelor research project.

Personal learning objectives

The majority of the personal learning objectives found in Table 13, were formulated after approval of the research proposal. This enabled me to gear the objectives towards the project. Several new learning points regarding project leadership and team work emerged during the project, so these are presented here as well. They are the last three entries in the table.

Competence	Learning objective	Performance
Scientific approach	Learn how to set up a scientific research project	Good
Effective use of scientific sources	Effectively and efficiently search for- and use scientific literature	Average
Scientific analysis	Use structured methods and substantiated arguments to make decisions	Very good
Setting priorities	Clearly setting priorities between what is essential for good results and nice to have.	Very good
Project planning	Plan activities and adjust planning according to actual progress to deliver results on time	Good
Professional communication	Keeping stakeholders informed with timely and relevant information	Good
Criticism	Use criticism constructively to improve solution quality and critically appraise feedback	Good
Leadership	Learn to motivate and steer a project group towards good results under time pressure.	Very Good
Teamwork	Learn to provide a platform for team members to contribute to their best ability	Good
Empathy	Learn to appreciate people's feelings and opinions in work related matters	Average

Table 13: Overview of learning objectives

Scientific approach

When starting this research project, it had been two years since I had last performed a research project. The main challenge was to formulate research questions that would result in the right information, without covering too much ground. It was very useful to thoroughly think about which information was required to solve the problem and translate them into questions. I believe I succeeded quite well after making a few improvements. For next time therefore, I hope to achieve the same quality in the research questions but quicker.

Effective use of scientific sources

The research questions provided good directions for searching for scientific literature. However, I have always found it difficult to find appropriate literature quickly and always needed more time than expected. This time was no different, as the most useful literature reviews surfaced when I was at the end of the period reserved for the literature review. This is obviously better than not finding them at all, but it would have saved valuable time if I had found them sooner, hence the average rating. I believe a search course or getting tips from experienced researchers could improve my speed for next time and because next time will be a master thesis that will definitely be worthwhile.

Scientific analysis
Analysing problems in a structured way and applying theoretical concepts to practical situations is usually one of my strengths. After completing the project, I am very happy with the way I have been able to use supporting data and theory to derive solutions. My supervisor at Aeronamic also complemented me for the sound argumentation and use of company data to explain choices. I also experienced during the project that convincing people of ideas is much easier this way. The best example is when I had to convince operators that dedicated assembly stations were not necessary. Their initial feeling was that changing this into flexible stations was stupid, but after seeing the data and hearing my arguments everyone agreed that it was the way forward. During project work at University or at Solar Team Twente, I usually tried to convince others by reasoning as well. Without facts however, this was much more difficult to achieve. I will definitely continue to present ideas and solutions backed up with data, whenever I am able to.

Setting priorities
I know myself to be a perfectionist. Sometimes in the past I have lost myself somewhat in details when doing projects, when those details did not matter yet in that stage of the project. I must say I surprised myself with regard to this learning objective. I believe my experience in Solar Team Twente really improved my setting of priorities because we were under immense time pressure then. That has helped me greatly during this project because I could quickly distinguish what was essential and which were ‘nice to have’ details. One example is that many operators continuously went into details on inventory locations and workbench layout very quickly, and that I had to continuously remind them that getting the overall layout right was much more important and that these details could be left till later. Nevertheless, I will always have to keep this in mind for the future, because it would be a shame to lose this competence and fall into bad habits again.

Project planning
It was very clear that I was responsible for the planning of the project right from the start. A kick off meeting was arranged, but after that I would have to arrange all meetings myself and function as a ‘project leader’ for the team. There was also considerable time pressure because management wanted the layout design ready by mid July. I think I performed reasonably well with respect to planning. I had set personal deadlines to report on my progress to the operators and management throughout the project. These kept the project moving forward and kept everyone engaged as well. We ended up performing the project largely according to schedule, with only minor variations along the way. I do have to admit that we did not encounter any setbacks during the project, so that made everything easier. All things considered, the project was performed on time without overtime at the end, so that indicates the project planning was sound.

Professional communication
Keeping management and all other stakeholders informed was important to keep support for the project up. I think I did quite well in informing the operators and management about the progress. This was made easier because I held several meetings with both, at the start of which I could always first set out the progress that had been made. Only once, did a member of senior management visit me to ask about progress, and that was at the end when I had had a meeting with him the day before. This shows for me that information was always sufficient and timely. The only group I could have informed better was the group of employees responsible for the building of the expansion. I did inform them regularly about the project, with the result that I had to make adjustments a few times. If I had kept them in the loop, then both our work would have been coordinated better and some adjustments might not have been necessary.

Criticism
The many discussions and meetings with the operators were very useful. They offered criticism more often than not, which caused me to always rethink my arguments. I had already learned to embrace

criticism prior to this project, and that helped me. Criticism from my supervisors was also very welcome and I always tried to think where the critique came from, so I could improve my work. Furthermore, I tried to generalise the criticism to see if there were more areas where that criticism applied. Being able to cope with- and learn from criticism is very important for my professional future, so I am happy that I am developing myself more and more in this area.

Leadership
This project was not the first time I had been a project leader with a team. It was the first time, however, with complete strangers and in an environment better known to the other team members than to myself. Despite this, the operators were very cooperative in all project meetings. I think not acting like a know it all, but asking for their expert opinion was instrument in that. I have also tried my very best to show them the benefits for any direction I wanted to go. I believe that showing that I thought about the consequences for them, motivated them to work with me instead of against me.

I also gave them plenty of own responsibility in the project. E.g. I asked three operators to design the detailed layouts fro the NDR and Repair sections. I think that because I had involved them intensively and asked for their opinions prior to that point, they were very happy to do this and I got those designs very quickly as a result.

Teamwork
There were different characters in the project group, and throughout the Aerospace Production Facility the diversity obviously increased. Some people felt comfortable speaking in the group sessions, others were more comfortable expressing their opinions in one-on-one conversation. There was also a difference in employees' susceptibility to new ideas. Unsurprisingly, the older employees were more resistant to change than the younger ones. It was worthwhile to experience that, and more valuable to see how they could be convinced. I already discussed that under 'scientific analysis'.

I also tried to be encouraging at all times, instead of inpatient during e.g. the brainstorm sessions. In this particular case, the outcomes were not always as creative as I had hoped at first, but after some perseverance, the participants learned how brainstorming worked. Again, one operator found it difficult to discuss his ideas publicly, while another was very comfortable throwing out ideas in the group.

Empathy
I must not exaggerate how much I developed this competence, but when trying to convince people of my ideas and confronting their arguments, I had to be careful not to overdo it. On one occasion, I had to hold back a bit when I thought an operator was being unreasonable. However, I could not tell him in front of his peers that his arguments were 'invalid', and that is putting it nicely. Instead, I went to speak to him in private and explained my point of view again, which I hope was appreciated. I also hope that I judged their feelings about certain things correctly, e.g. by continuing with dedicated assembly stations into scoring, even though I had strongly argued for the flexible assembly stations.

Process evaluation
Now follows a brief evaluation of the process of performing this research project. Different steps have been distinguished for this purpose.

Acquiring the assignment
Acquiring the assignment went very well at first. I had quickly found a company willing to provide me with a Bachelor thesis opportunity. However, we dawdled on formulating a definitive assignment for quite some time. At this time, I did not have a supervisor at the university yet. After turning the still vague assignment into a research proposal in the first week of the internship, this first assignment was not found suitable for a Bachelor thesis. Formulating a new assignment eventually caused for three weeks of delay. I learned from this experience that making clear agreements before starting an internship is very important. It is also very important to have a supervisor at university to help during this first phase. I believe it is actually the most difficult phase because it has the most ambiguity.

Research proposal

At the second time of asking, drawing up a research proposal went very well in my opinion. I spent enough time on it to accurately define the scope of the research and this gave me a good ‘second start’ after the initial delay.

Theoretical framework

Moving on from the research proposal to creating the theoretical framework for the project was not difficult. I knew what I needed to find to help me solve the research questions. However, actually finding that information proved difficult. I already discussed part of this under ‘Effective use of scientific sources’. A second difficulty was that the company was very eager to get started. That meant the project was given a kick off meeting straight away and that management expected me to get stuck into interviews and process analysis straight away. Having to hold that enthusiasm off was difficult, but I do not really see how I could have changed this.

Designing

The design process was a lot of fun. I had prepared it well by first clearly defining criteria and constraints, and deciding on a conceptual layout. Because it had taken a while to get to the design phase, everyone in the project team was happy to start. The good preparation led to the design process itself taking less time than expected. So, stating the obvious with a Dutch expression, good preparations mean half the job is already done. The brainstorms and feedback sessions also went very well. I got useful feedback and it gave me the opportunity to show actual progress.

Writing the report

I have previously written a report for the completion of my minor International Management. I had left writing till after the completion of the project and it dragged on for a long time. This time, I wrote my report as the project progressed. This meant I had to revise sections from time to time, but also reduced the amount of writing at the end. Writing reports this way definitely works for me, so I will continue to do it this way in the future.