Scania CV AB

Exploring including ergonomics in the assembly line balancing process: a test case

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An industrial engineering and management master thesis project at Scania CV AB

UNIVERSITY OF TWENTE.

SCANIA

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Management summary

Scania CV AB is a global manufacturer best known for its heavy trucks. We investigate the possibilities for Scania to improve their balancing process by including ergonomics. The core problems we uncovered are the lack of simulated ergonomic assessments and the lack of support in the currently used software tools for multi-objective balancing and automation. Therefore, we aim to develop a suitable and improved balancing process for Scania's assembly line, solving the problem of the suboptimal (i.e. single-objective and manual) balancing process and including the aspect of ergonomics.

Scania's truck assembly process consists of an S-shaped assembly line with approximately 45 stations. The assembly line accommodates the production of many different variants of trucks, owing to the modular system of truck design. Based on the customer demand and orderbook, the assembly line is assigned a takt time; the time in which each of the stations must finish all its tasks. The assembly line balancing process encompasses the activity of assigning all the assembly tasks to stations. This process is executed manually in a software program called AviX. Currently, the only objective taken into account when rebalancing the assembly line is productivity. The working conditions of the operators along the line, specifically the physical aspect of ergonomics, are assessed after a balance has been created. These assessments are done by ergonomists observing the motions of an operator during a takt, and takes around 4 hours per operator per truck passing through.

We research the improvement of the balancing process using a pedal car test case (PCTC) with two variants and the publicly known ergonomic risk assessment method Rapid Entire Body Analysis (REBA). We explore the possibilities of including simulated ergonomics assessments in the balancing process. This is done using the Industrial Path Solutions software package Industrial Moving Manikins (IMMA). This software allows the simulation and ergonomic assessment of human motions. We decide to ergonomically assess the simple walking tasks in AviX manually, and to simulate the tasks that are more complex than walking in IMMA. A connection between AviX and IMMA is established to ensure easy data exchange. Finally, each task in AviX has its own REBA score, and a combination of tasks yields a time weighted average REBA score. The view in AviX is displayed in Figure 1.

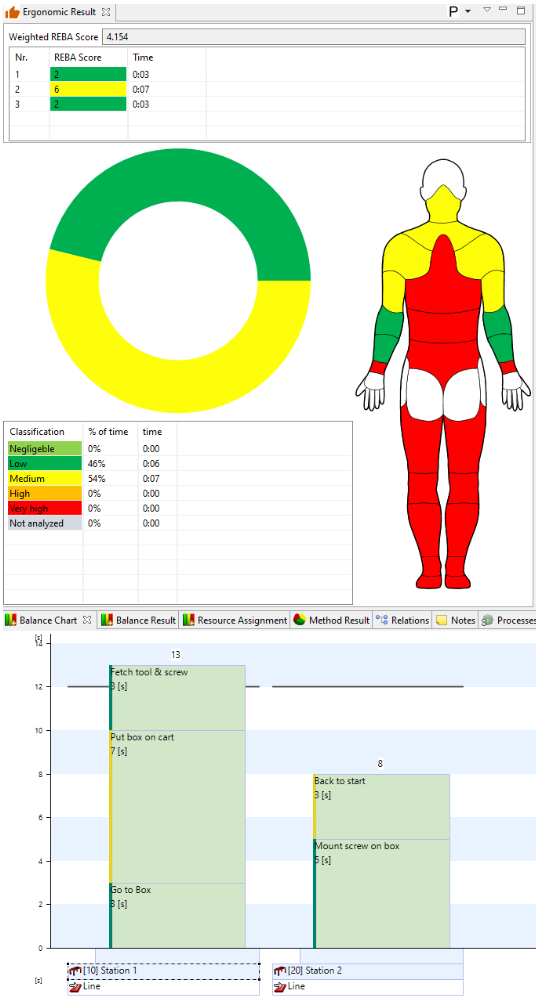

Figure 1. New layout of AviX Balancing including Ergonomic Result

Using the gathered ergonomic data, we explore both an improved manual balancing approach, and two automated balancing approaches. The manual approach consists of conducting experiments with various process engineers. They balance the PCTC using a provided precedence graph in three parts: balancing without ergonomic data (A1), afterwards re-balancing based on ergonomic feedback (A2), and finally balancing including the ergonomic data (B). We assess the performance in terms of cycle time (CT), overall ergonomic risks (SUM) and peak ergonomic risks (MAX). Table 1 shows the best objective scores that were achieved by the participants for each experiment.

Table 1. Manual approach: Best achieved objective values per experiment

Objective	MIN CT	MIN SUM	MIN MAX
A1	112.5	8.909	3.181
A2	113.2	8.978	3.157
B	113.8	8.603	3.020

We observe an increase in CT and a decrease in MAX values over the different experiments. To explore whether the differences in these manual results between the experiments are statistically significant, we conduct a Wilcoxon matched pairs signed ranks test with $\alpha=0.05$. These tests show that the inclusion of only ergonomic feedback (A2) does not provide significantly lower ergonomic risks than the initial balance (A1). However, the inclusion of ergonomic data in AviX (B) yields significantly better ergonomic results when compared to the experiment without any ergonomic input (A1), both peak ($p=0.000$) and overall ($p=0.013$). Similarly, we see a significant reduction in peak ergonomic risks ($p=0.003$) over the assembly line when comparing experiment B to A2.

The automated approaches consist of an exact method and a metaheuristic. More specifically, we explore a mixed integer program (MIP) and a genetic algorithm (GA), respectively. The MIP is adapted from previous research and yields good results, but the complexity of the case makes it impossible to know whether these results are optimal: the MIP was time capped at 20,000 seconds, around 5.5 hours. The GA is developed to find near-optimal solutions in less time (approx. 1 hour for 10 runs). The pareto frontiers of all approaches (manual, MIP and GA) are shown in Figure 2 (CT & SUM) and Figure 3 (CT & MAX). When comparing the GA results to the MIP, we see the GA reaches slightly inferior results than the MIP. We conclude the GA is most time-efficient while only yielding slightly worse results. Moreover, we also compare both results to the manual experiment results, and this shows an automated approach is preferred in terms of cycle time and ergonomic performance.

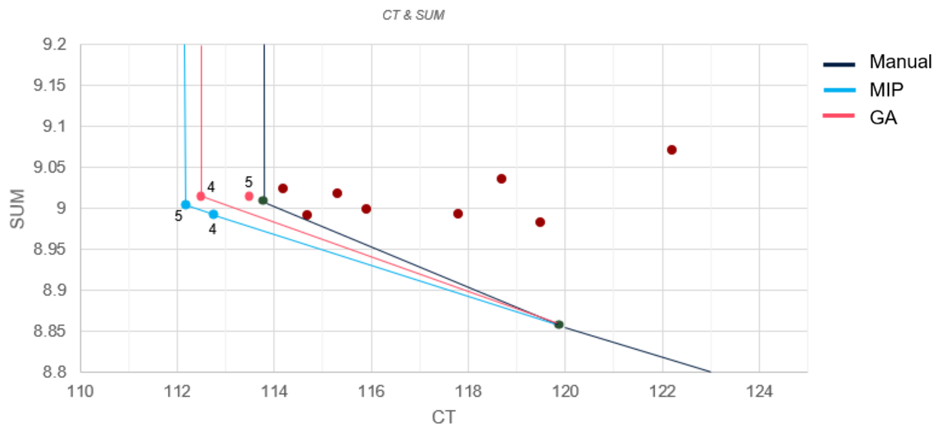

Figure 2. PCTC experiment results: pareto frontier of CT & SUM objective combination

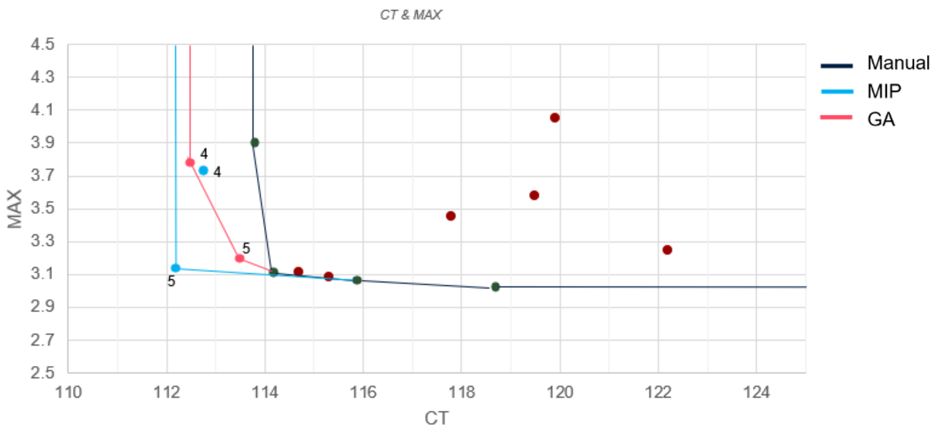

Figure 3. PCTC experiment results: pareto frontier of CT & MAX objective combination

To assess the approaches, however, we must also include the aspect of practical applicability: whether these approaches can be scaled from the PCTC to the truck assembly line balancing process. The ergonomic data gathering process would require small software changes to be implemented at Scania but is very close to maturity. Moreover, the time spent is similar to the current ergonomic assessment time, but the task-based aspect of our approach requires less re-assessments when rebalancing. The manual balancing process as explored also requires some changes, but since the software is almost mature, this approach is also soon applicable. The automated approach, however, is quite immature. The specific and elaborate data required to perform the automated balancing is a big limitation of this approach. Most of the data concerning precedence relations and zoning are not currently documented and are assessed by personal expertise of operators in the current process. Both for the exact and metaheuristic approaches, realistic complexities such as multiple operators per station would need to be incorporated, as well as a considerably larger set of tasks. In contrast, the manual method could include these complexities more easily, by training process engineers to take these into account.

We foresee many benefits from both the simulated ergonomic assessments and the manual multi-objective balancing approach and conclude that it is worthy of further developing and finetuning for implementation. Therefore, we recommend Scania to start preparing for the implementation of the ergonomic data gathering method and the manual multi-objective balancing approach, including ergonomics. The conclusion of the automated approach is that more research is necessary. Thus, we recommend conducting further research into the automated approaches, by including more complex test cases. These recommendations are summarized in the roadmap shown in Figure 4.

Figure 4. Suggested implementation roadmap

Preface

Before you lies the final product of my master's in Industrial Engineering & Management at the University of Twente. During this master programme, I have thoroughly enjoyed my time in Enschede and am very grateful to have made some great friends along the way.

When looking for a thesis project, it was my goal to not only present you with a good thesis report, but also to acquire experience with working and living abroad, in an international environment. However, the current pandemic almost threatened this goal. Nevertheless, I got the great opportunity to go to Södertälje, Sweden, to do my project at the Smart Factory Lab of Scania. Despite the pandemic and social distancing, I have felt a very warm welcome from the Smart Factory Lab team, and I am very grateful to have been able to join them for five months.

I hereby want to thank my supervisors from the University of Twente, Marco Schutten and Peter Schuur, for their support and guidance. They were very supportive in supervising my thesis project from another country. I am grateful for the good conversations we had and for their feedback, which undoubtedly has made me perform much better than I ever could have on my own.

Next, I want to thank Scania and its Smart Factory Lab team, for creating such a friendly, welcoming and innovative atmosphere, where it seems like anything is possible. I will carry great memories from my time in Sweden and the international working environment I got to enjoy. More specifically, I would like to thank Juan Luis Jiménez Sánchez, for his support and motivation while supervising my thesis project. I would also like to thank Lars Hanson, for the ergonomic expertise and the passionate discussions about the project's processes. In addition, I would like to thank the research project of VF-KDO, specifically Amir Nourmohammadi, for all the support in executing my research.

Last but not least, I want to thank my family and friends, who have supported and encouraged me at all times. The uncertainty and limitations of the pandemic made the thesis project, usually already challenging, even more demanding. Without your uplifting words of support and understanding, it would have been a much harder task than it was today.

Finally, all that remains is to proudly present my thesis to you. I hope you will enjoy reading it!

Janneke Vollebregt

April 6, 2021

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List of abbreviations

Abbreviation	Definition	Introduced on page
VF-KDO	Virtual Factories - Knowledge Driven Optimization	1
SES	Scania Ergonomic Standard	2
ALBP	Assembly Line Balancing Problem	4
SAMS	Scania Assembly Master Sequence	6
CT	Cycle time	9
WACT	Weighted Average Cycle Time	11
PS	Position Standard	11
KPI	Key Performance Indicator	12
RULA	Rapid Upper Limb Assessment	13
REBA	Rapid Entire Body Assessment	14
SALBP	Simple ALBP	16
GALBP	Generalised ALBP	16
MMALBP	Mixed-model ALBP	16
GA	Genetic Algorithm	17
NP	Non-deterministic Polynomial-time	19
PCTC	Pedal Car Test Case	20
IPS	Industrial Path Solutions (software)	21
IMMA	Intelligently Moving Manikins (tool)	21
TWAR	Time-Weighted Average REBA	26
MIP	Mixed Integer Program	30
TS	Task Sequence	35

1 Introduction

Scania AB is a global manufacturer best known for its trucks, that also produces busses, coaches and power solutions for industrial and marine equipment. In 2019, Scania's vehicles market share in Europe was at its highest point ever: 18.7% (Scania AB, 2019). This project takes place at Scania in Södertälje, Sweden, where their headquarters are situated. In Södertälje, Scania also houses the R&D department, an assembly line and several component factories. Scania's Smart Factory Lab is an innovation-focused department which is situated in the assembly line building. It has an '*experimental test environment that explores, assesses and pilots new technologies*' (Scania AB, 2019). This lab aims to adopt new technology for the production processes sooner by being in touch with the academic world and supplier innovations. Innovations are explored and tested in the lab so see if they fit into the manufacturing and assembly Scania executes. The Smart Factory Lab employs around 15 engineers, thesis workers and trainees from around the world (Scania AB, 2019).

Scania is currently involved in a collaboration with the University of Skövde and their research project VF-KDO. VF-KDO stands for Virtual Factories with Knowledge-Driven Optimisation and explores the many options of simulation and modelling in the optimisation of factory processes (VF-KDO, 2019). Both Scania and the University of Skövde are also partners in the MOSIM project. This project concerns Human Simulation Modelling for ergonomics and efficiency purposes in production environments (MOSIM, 2018). Scania is involved in these research projects and their results but wishes to integrate these fields of research and find the application possibilities in their production process. To do this, Scania needs both academic knowledge and a vision for practical application, which takes its shape in the form of an Industrial Engineering and Management Master student, conducting their thesis project on this subject.

We define the problem statement in Section 1.1, followed by the problem context in Section 1.2. We elaborate on the core problem in Section 1.3. We demarcate the research by providing a research problem in Section 1.4 and the research questions in Section 1.5.

1.1 Problem statement

Scania produces trucks (and busses) with a modular approach. This gives the customers many options to fit the vehicles to their needs, while still enabling Scania to standardize the process. However, this modularity still yields a large variety in the production and assembly process of these vehicles. Thus, Scania requires a good balancing system to operate the line assembly process smoothly (Scania AB, 2018). The problem of Scania Production is that the balancing system they currently work with is a manual system and only takes into account one objective at a time (J.L. Jiménez Sánchez, Project Engineer, personal communication, May 13, 2020).

The balancing process must be improved, to create a more efficient planning process, which will result in a more efficiently used production line capacity. Currently, several parallel projects are conducted internally and externally, making this the right moment to improve the balancing system by looking at automatic and/or multi-objective balancing (J.L. Jiménez Sánchez, Project Engineer, personal communication, June 17, 2020).

1.2 Problem context

The problem addressed in this project is centred around Scania's assembly process for trucks. The mentioned modular approach and the fact that the different models and configurations of trucks will be assembled on one assembly line makes this a Mixed Model Assembly Line Balancing Problem (MMALBP); see Chapter 3 for more information on this classification. As mentioned, the aim of this research is to find a more efficient balancing system and balancing process by automation and solving the balancing problem for not one, but multiple objectives at a time. The current balancing process takes up more resources and performs worse than desired.

The current objective is productivity, indicating a minimisation of the used time to assemble a truck. A tool is used for the process balancing, but the process engineer eventually manually rearranges the tasks between stations until productivity is satisfactory. However, maximising productivity is not without consequences. When executing the balancing process strictly looking at assembly line productivity, the workload distribution could lead to unacceptable ergonomic situations. The concept of ergonomics considers the line operators' movements in executing their tasks (Wickens, Gordon, & Liu, 1998). If a movement is deemed physically impossible or is potentially harmful for the body of the operator, it is ergonomically irresponsible. Assuming the tasks in themselves are ergonomically acceptable, such ergonomic issues can arise if combinations of tasks are not in line with the ergonomic standard, specifically the Scania Ergonomic Standard (SES). Thus, a second objective that Scania wants to employ is an optimal level of ergonomics (J.L. Jiménez Sánchez, Project Engineer, personal communication, August 11, 2020).

Figure 1-1. Pedal Cars used for training at Scania Assembly

As mentioned, Scania's Smart Factory Lab is concerned with the improvement of production processes by innovation in close contact with the academic world. Thus, the Smart Factory Lab initiated the research into improvement of the balancing process. However, case studies are often very complex and/or contain strategic and confidential information on products and company processes. Therefore, Scania uses a pedal car (see Figure 1-1) for process-related research and training activities worldwide (J.L. Jiménez Sánchez, Project Engineer, personal communication, June 30, 2020). In this project, the balancing system is improved based on the use of the test case of a pedal car assembly process.

The problem cluster in Figure 1-2 visualises the problem context. It shows the root causes that we address in this thesis project in blue. The yellow problems are reduced or eliminated by this research. The red elements in this figure are uncontrollable by this project.

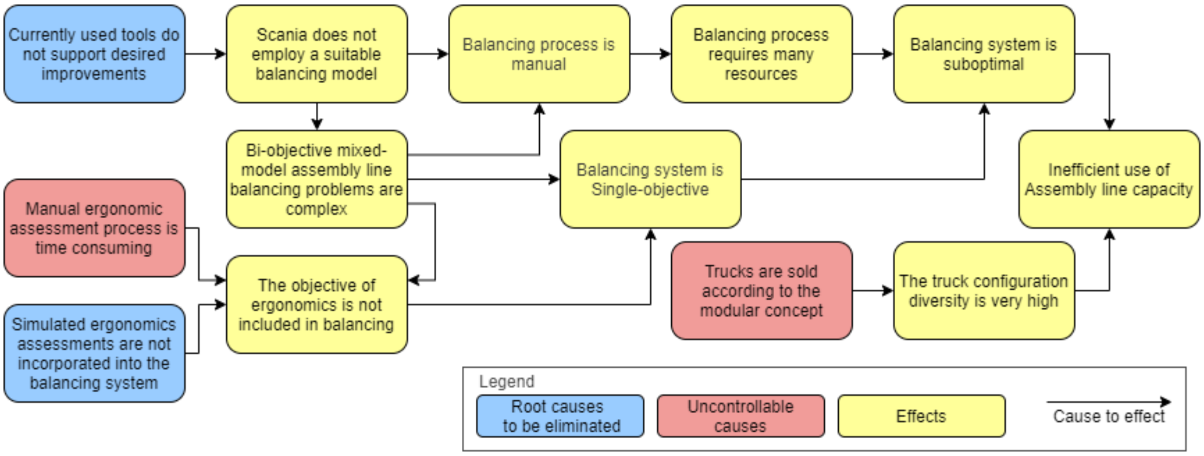

Figure 1-2. Problem Cluster

1.3 Core problem

As shown in the problem cluster in Figure 1-2, the problems we solve lie fully upstream of the cluster and are considered the root causes, also called core problems. Thus, we extract the core problem statements for this research:

- ***Simulated ergonomic assessments are not incorporated into the balancing system***
- ***The currently used software tools do not support automation and multi-objective balancing***

We made decisions concerning the scope of the master thesis project:

- The project is focused on improving the process of re-balancing activities, thus involving minimal changes to the number of workstations, their layout, etc.
- In this project, the multi-objective balancing involves just two objectives: productivity and ergonomics.

We solve the core problem mentioned above in the time span of this project alone. The next section further demarcates the goal of this project.

1.4 Research problem

The knowledge required to solve the problem of Scania's suboptimal assembly line balancing process consists of knowledge concerning the assembly process itself and the current assembly line balancing process. Moreover, knowledge is required concerning possible solutions, involving which balancing tools, methods and models are suitable specifically to the assembly process of Scania trucks. Finally, based on Scania's pedal car test case, knowledge is acquired concerning which of the possible solutions yield the best improvement results.

Thus, the research goal of this thesis project is:

To develop a suitable and improved balancing process for Scania's assembly line, solving the problem of the suboptimal (i.e. single-objective and manual) balancing process including the aspect of ergonomics.

1.5 Research questions

We define research questions to solve the research problem. These questions consider different aspects of the research and together provide the solution for the core problem mentioned previously.

To be able to provide Scania with suitable and useful results, we investigate the current situation of Scania first. We execute this investigation by reviewing Scania's internal process descriptions and by conducting interviews with relevant persons involved. Chapter 2 describes the answers to the questions:

1. **What is the current situation of Scania regarding the assembly and assembly line balancing processes?**
   1.1. What is the current assembly process of Scania?
   1.2. What is the current assembly line balancing process of Scania?
      1.2.1. What objectives are currently used for the assembly line balancing?
      1.2.2. What steps does the current assembly line balancing process consist of?
      1.2.3. Which assembly line balancing process Key Performance Indicators (KPIs) are measured currently and what is their value?

The second question considers the current knowledge in literature concerning assembly line ergonomics and assembly line balancing problems (ALBPs). We answer the question and sub questions by executing a general literature review and exploring the articles produced as results of the VF-KDO and MOSIM projects. We use the problem context (Section 1.2) and the general known situation of Scania (Question 1.2) to funnel the literature review towards the most relevant field for this research. Chapter 3 provides the answer to the question and its sub questions:

2. **What is currently known about assembly line ergonomics and assembly line balancing problems?**
   2.1. What is currently known about assembly line ergonomics?
      2.1.1. What is ergonomics?
      2.1.2. What are well known assessment methods for assembly line ergonomics?
   2.2. What is currently known about ALBPs?
      2.2.1. What are the different types of ALBPs?
      2.2.2. What type of assembly line balancing problem fits the general case of Scania's assembly line?
      2.2.3. Which methods are commonly used to solve Scania's type of ALBP?

The third research question combines the practical situation with the literature review and establishes the possible approaches. Before attempting to include another objective in the balancing process we must explore which data gathering activities are required. For Question 3.1 we consult stakeholders and explore the possibilities of gathering the required information. A first balancing approach is to combine the two objectives in the manual balancing process. To answer question 3.2, we consult expert stakeholders of line balancing and both ergonomics and productivity to establish a new assembly line balancing process concept. Question 3.3 addresses another solution: to automate the assembly line balancing process. To answer sub questions 3.3.1 and 3.3.2, we collaborate with the VF-KDO project, consult stakeholders and conduct interviews to establish the best methods for the improved assembly line balancing process. We also include a comparison of the executed literature review with the answers to previous questions, yielding the answer to these sub questions. Chapter 4 contains the answer to the questions:

3. **Which approaches can improve Scania's assembly line balancing process by including the ergonomics objective?**
   3.1. How can we adapt the available data to facilitate the inclusion of the ergonomics objective?
   3.2. How can the balancing objectives of productivity and ergonomics be combined in the manual assembly line balancing process?
   3.3. Which automated options are suitable to automate Scania's assembly line balancing process optimising the productivity and ergonomics objectives?

The fourth research question describes the translation from Scania's actual process to the pedal car test case. We answer this sub question by conducting interviews with relevant persons involved and by executing experiments to compare the current situation and alternative approaches, using the pedal car test case. Chapter 5 provides the answer to the questions:

4. **What is the performance of the current process and alternative approaches when applied on the pedal car test case?**
   4.1. To what extent can the pedal car test case be used for testing the suitability of an approach for Scania's actual assembly line balancing process?
   4.2. What is the performance of the manual approach?
   4.3. What is the performance of automated approach?

The final research question considers the options for implementing the approaches into Scania's assembly line balancing process. We answer this question by analysing the gap between the required time, knowledge, hardware and data for the different approaches, and those available. We answer the following research question in Chapter 6:

5. **How can the best performing approach for the pedal car test case be implemented in Scania's truck assembly line balancing process?**
   5.1. What adaptation needs to be made in the approach to scale up from the pedal car test case to Scania's actual assembly line?
   5.2. What is the expected performance improvement of the balancing process when the new approach is applied?

2 Scania's current situation

This chapter provides the answer to the first research question: "What is the current situation of Scania regarding the assembly and assembly line balancing processes?". We describe the general assembly process of Scania trucks in Section 2.1. Subsequently, Section 2.2 contains Scania's assembly line balancing process with its objectives, steps and current performance.

2.1 Scania's assembly process

The assembly process of Scania trucks is where all the truck parts come together and are assembled to make a finished and fully functioning truck. Assembly lines come in multiple shapes and forms. Scania's assembly line is driven, which means the unfinished product moves at a fixed speed through the line and is being assembled while on the move. The assembly line in Södertälje (see Figure 2-1) has an S-shape, to optimally make use of the building's space. However, the general assembly line is linear in terms of operations, which means each workstation has their own operators and tools. The stations require parts and materials that are supplied by Scania's own plants or external companies. The general assembly line is surrounded by strategically positioned preassembly stations which provide the moving line with a steady flow of preassembled parts, reducing the time spent on the moving line (L. Hanson, Team Leader SFL, personal communication, October 13, 2020).

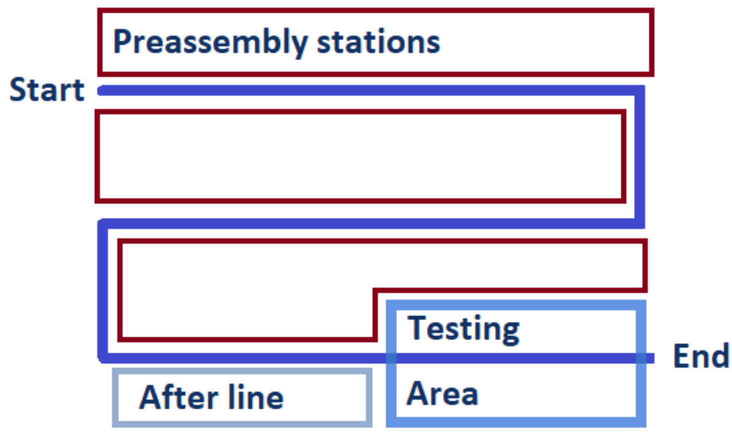

Figure 2-1. Sketch of assembly line layout

Since Scania's assembly line is driven by customer demand, Scania establishes a takt time. This means that the demand level (averaged over a period of time) defines how many trucks should be made in the available time (J.L. Jiménez Sánchez, Project Engineer, personal communication, August 11, 2020). At Scania, the demand can be fulfilled from four different general assembly plants, located in Södertälje (Sweden), Zwolle (the Netherlands), Angers (France) and Sao Paolo (Brazil). The actual production level of each of these plants is defined by the logistics planning department. The front office technicians of an assembly plant then define the takt time by taking the number of trucks to be produced per day and adding stop time margins (K. Svensson, Process Engineer, personal communication, October 8, 2020). The takt time itself indicates the time a truck stays at each station, which is equal to the time between each truck leaving the assembly line fully finished (Theisens, 2016). In this research, we see the takt time as a given and assume it is fixed and feasible (within plant capacity limits).

For each general assembly plant, Scania tries to stick to the Scania Assembly Master Sequence (SAMS), a document that contains the general tasks that must be executed to assemble the trucks and their sequence. Not all general assembly lines are the same, however, due to variations in (amongst other things) location, building size or layout. The SAMS is used throughout the organisation but is especially useful for the designers. Using this document, they can assess at which station a change will affect the assembly line; for example, when introducing a change in a part's design. The SAMS shows the assembly lines are expected to have around 45 assembly stations, divided over 13 areas. The areas in this document are based on the physical access the operators have to the unfinished truck. This physical access can be limited by the position of the unfinished truck (frame upside-down, lifted higher, cab tilted, etc.), by ergonomic standards and/or by previously assembled components blocking access. Moreover, each of the stations' general tasks have a predefined position: front, left-hand front, right-hand front, left-hand rear, right-hand rear and rear. This indicates in which position an operator is situated during the execution of the task but does not affect the number of operators assigned to a station (J. Karlsson, Senior Engineering Advisor, personal communication, September 7, 2020).

As mentioned in Section 1.1, Scania uses a modular approach for providing customers with trucks that fit their needs. Figure 2-2 illustrates the modular system in general.

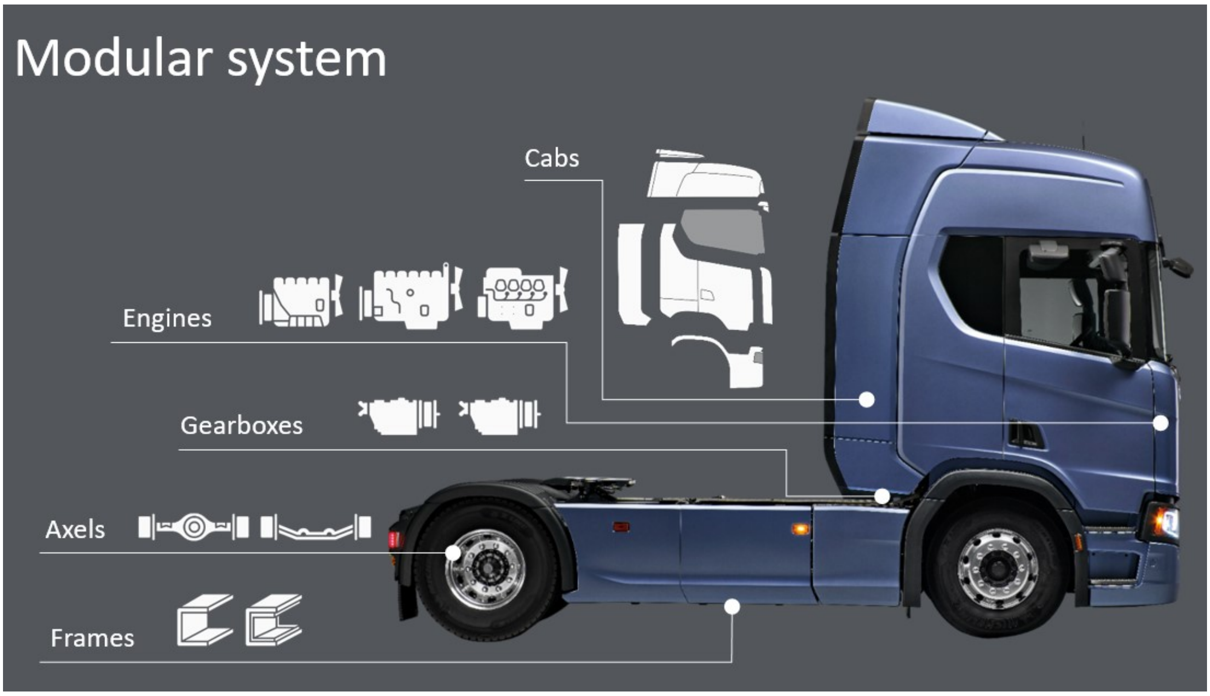

Figure 2-2. Modular approach Scania trucks

However, this figure does not show the detail of each of the modules. For example: besides the type of axle, a truck can have between two and five axles which can be driven or non-driven, steering or non-steering. The online Scania configurator[1] shows seven-wheel configuration options for a long-distance tractor-type truck (pulling a trailer) with general cargo, and fourteen-wheel configuration options for a similar but rigid-type truck (which will have a body installed). This means that only considering the truck type and wheel configuration, already 21 different trucks could be assembled on one line (Scania, 2020).

Thus, many different possible combinations of modules are produced, leading to a make-to-order production approach. This make-to-order approach means that all the trucks that are assembled on the production line are sold and produced for a specific customer. Therefore, the assembly line needs

[1] The Scania configurator varies according to the country, since national regulations might affect the types of trucks allowed. This example is based on the Dutch version.

to be flexible enough to deal with uncertainty, both in terms of total demand and demand per model (Slack, Brandon-Jones, & Johnston, 2016).

Besides the assembly line itself, some of the aforementioned variation of trucks on the assembly line is reduced by the 'After line' area. This area executes nonstandard tasks that are impossible to integrate into the assembly line process due to infrequent occurrence, complexity, time constraints and/or the requirement of specialist tools (J. Karlsson, Senior Engineering Advisor, personal communication, September 7, 2020).

2.2 Scania's assembly line balancing process

We first describe the concept of line balancing in general. In the following sections, we describe the current situation of the assembly line balancing process of Scania trucks according to its objectives, its process steps and its performance.

Thomopoulos (1967, p. B59) defined line balancing as "*a procedure of assigning work to assembly operators in such a manner as to balance the work assignments among the operators*". Gosh and Gagnon (1989) state: "*The fundamental line balancing problem is to assign tasks to an ordered sequence of stations, such that the precedence relations are satisfied and some measure of effectiveness is optimized*". A more general definition describes line balancing as even work time allocation (Slack, Brandon-Jones, & Johnston, 2016). Most definitions agree that the concept of line balancing consists of (re-)arranging tasks along a linear process to achieve a smooth flow of operations with an optimised effectiveness measure (Fathi, Nourmohammadi, Ng, & Syberfeldt, 2019; Manavizadeh, Rabbani, Moshtaghi, & Jolai, 2012; Nourmohammadi, Fathi, Zandieh, & Ghobakhloo, 2019). We elaborate on line balancing in Chapter 3.

2.2.1 Objectives

To understand Scania's assembly line balancing process, the objectives must be clear. Currently, the process engineers employ one objective during the balancing process: productivity. This objective means Scania wishes to execute the assembly of each type of truck on the assembly line as fast as possible, minimising the total time spent (J.L. Jiménez Sánchez, Project Engineer, personal communication, June 17, 2020). This objective fits with Scania's make-to-order strategy since a longer assembly time could increase the delivery period for customers. Since the balancing takes place with the defined takt time, the best productivity is achieved when idle time is minimised. Process engineers aim for the operators to be busy between 90% and 100% of the total takt time (K. Svensson, Process Engineer, personal communication, September 10, 2020).

2.2.2 Process steps

The process of balancing Scania's assembly line is done in multiple steps. However, data is required before the balancing process can start concerning which tasks the assembly of each type of truck consists of, what the precedence relations are and how much time each task takes.

Precedence relations are requirements to the sequence of the separate tasks' execution. Figure 2-3 shows an example where task C cannot be executed until tasks A and B have been finished (Winston, 2004, p. 432). A more practical example: the wheels of a truck cannot be attached before the axle has been fixed to the chassis. During final assembly of a truck, these precedence relations exist between almost all tasks and can be different for each truck configuration.

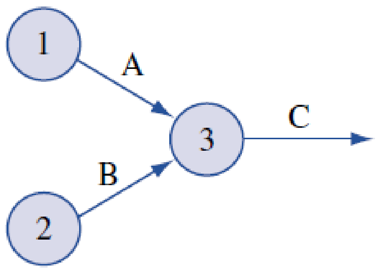

Figure 2-3. Example precedence relation (Winston, 2004, p. 432)

The general tasks and the precedence relations are defined in the SAMS. This document is a guideline and the different general assembly locations can divide tasks differently. Thus, the precedence relations balancing input consists mostly of the expertise of the operators on the assembly line, who guide the process engineers through shifting tasks around (K. Svensson, Process, Engineer, personal communication, September 10, 2020). The third dataset, the timing of each task, is collected by measuring the time spent using the Scania Time Settings methodology, a type of methods-time management (J.L. Jiménez Sánchez, Project Engineer, personal communication, June 17, 2020).

Once all these data are collected, the process is executed. The balancing process is done manually by Scania's process engineers. A software tool called AviX is used to easily rearrange tasks between stations and show the effect on the balance. AviX is a tool that has been used by Scania since 1997, but only recently has been incorporated as the standard way of (re-)balancing. The general tasks set from SAMS (applicable to all general assembly lines) is put in a local database in AviX and sent to the assembly plants. Most value adding activities are in this general task set, but the equipment used, distances walked etc. can vary between the different assembly plants and thus must be added manually for each plant (J.L. Jiménez Sánchez, Project Engineer, personal communication, June 17, 2020).

Figure 2-4 shows part of the pedal car task division in an AviX balance chart. The x-axis represents the workstations and the y-axis shows the total time in seconds. The bar for each position (or workstation) is composed of separate blocks, one for each task. The total time of all the tasks in the position, also called the cycle time (CT), is shown at the top of the bar: 149.3 seconds for position 1 and 151.4 seconds for position 2. The takt time in this case is set to 151 seconds, shown by the horizontal line in the graph. This makes it easier to see when the CT of a position exceeds the takt time, as is the case in position 2. However, the pedal car assembly has two variants: the black pedal car ('Svart bil') and the red one ('Röd bil'). In Figure 2-4, both are aggregated into one chart.

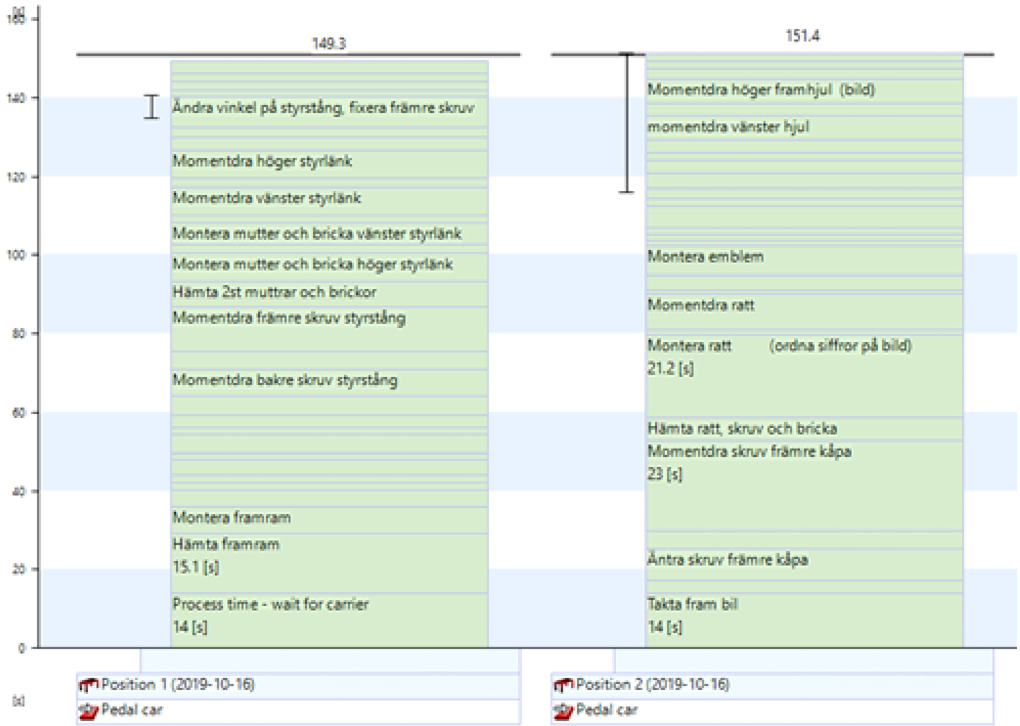

Figure 2-4. AviX' overall balance chart example

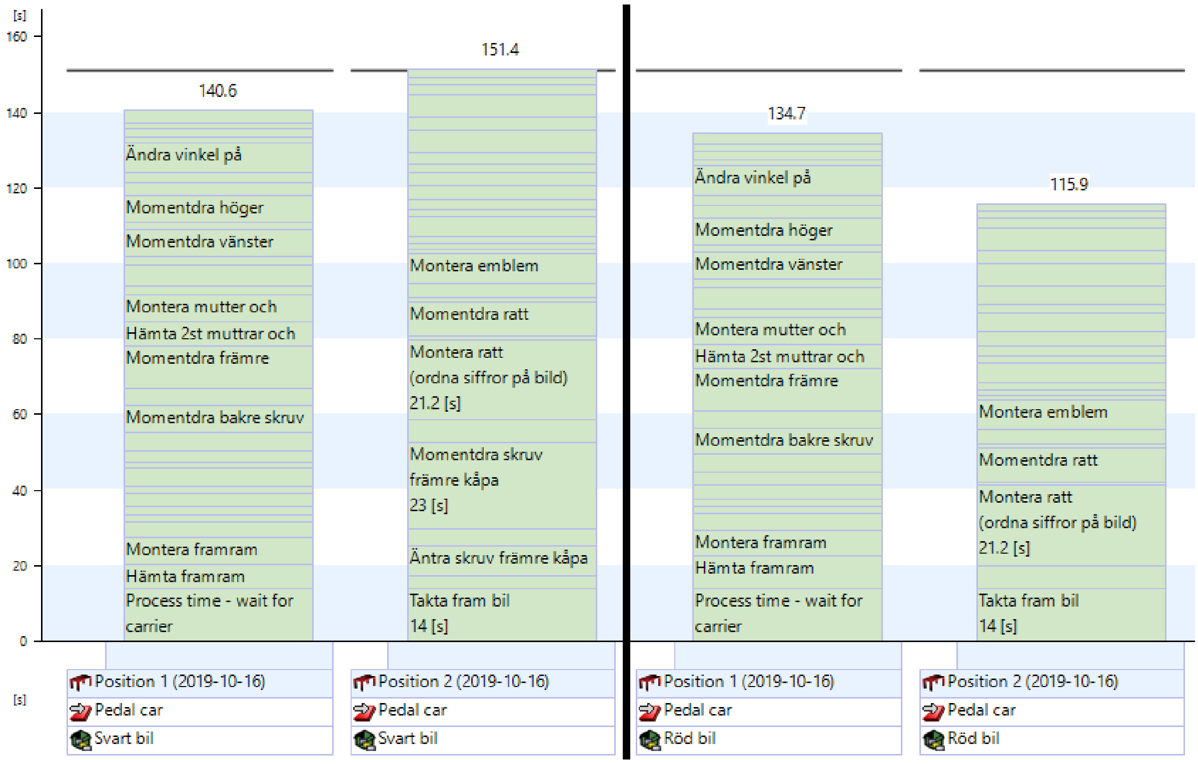

Figure 2-5. AviX' balance chart comparison of both variants of pedal car

Figure 2-5 shows the balance chart of both variants separately: black on the left and red on the right. The two variants are discerned in AviX by adding variant codes to the tasks if the task is specific to a variant. The charts shown in Figure 2-5 are thus the variant code filtered versions of the aggregated chart (in Figure 2-4). These charts show that the CT of the black pedal car exceeds the takt time in position 2, but the red pedal car does not. Thus, depending on the frequency of occurrence of the two pedal car variants, the workload at the second position might be acceptable despite exceeding the takt time.

However useful, AviX itself does not optimise the balancing result or check the feasibility in any way. The process engineers manually aim for the work to be distributed over the assembly line with maximum productivity (J.L. Jiménez Sánchez, Project Engineer, personal communication, June 17, 2020). Aiming for maximum productivity means that the takt time of a station is used productively and has minimal idle time. The process engineer creates a preliminary station balance in AviX that encompasses all tasks for all truck variants on that station. The truck 'variants' can be any variation, from entire truck model ranges to a customer-specific part. Subsequently, the frequency of the variants on that station are considered by copying the different variants and their cycle time and frequency into a Weighted Average Cycle Time (WACT) Excel file. Formulas in this file, as the name implies, then calculate the frequency weighted average of all the variants' CTs on the station. Process engineers aim for this WACT to be between 90% and 100% of the total takt time (K. Svensson, Process Engineer, personal communication, September 10, 2020). Figure 2-6 illustrates the flow of the current assembly line balancing process.

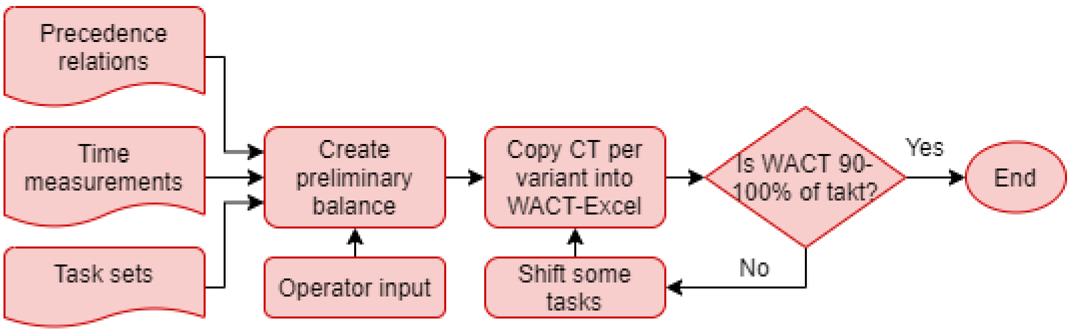

Figure 2-6. Flow of current assembly line balancing process

The frequency of re-balancing the assembly line is estimated to be between once every two months and once every few weeks, depending on the situation. Reasons for re-balancing are changes in the takt time, the continuous improvement mentality of Scania or ergonomic issues that arise during production (J.L. Jiménez Sánchez, Project Engineer, personal communication, August 11, 2020; K. Svensson, Process Engineer, personal communication, September 10, 2020).

As can be seen in Figure 2-6, no ergonomic aspect is currently considered during the balancing process. Scania has access to a specific digital human modelling software tool called IPS-IMMA (see Section 4.1), which can simulate the ergonomics of the process and evaluate them, but it is not widely used today. Thus, most of the ergonomic evaluations are currently done by physically going to stations and assessing operator motions (J.L. Jiménez Sánchez, Project Engineer, personal communication, June 17, 2020). An ergonomic analysis of one position standard (PS), one operator during one takt, takes around 4 hours (S. Tekeli, Ergonomist, personal communication, September 22, 2020).

Being so time consuming, two ergonomists reveal that not all PSs are analysed (J. Sandblad, Ergonomist, personal communication, September 14, 2020). For example, of all 500 PSs in Scania Production Zwolle, only 90 have undergone ergonomic analysis. Mostly, these analyses are done on request when an operator is suffering from discomfort or pain during or following the execution of their tasks. In addition, the ergonomic analysis of a PS cannot encompass all variants that are assembled at that position; thus, the analysis is done considering the most occurring variant. For less frequently occurring variants, an analysis can be done only on specific request (S. Tekeli, Ergonomist, personal communication, September 22, 2020).

2.2.3 Key Performance Indicators

As mentioned, the process engineers employ only the balancing key performance indicator (KPI) of the CT as a percentage of takt time, which is aimed to be between 90 and 100%. No ergonomic KPI is currently employed for the balancing result. However, the current assembly line balancing process itself does not employ any KPI's. Thus, the performance of the current balancing process is difficult to measure.

An improvement aspect of the current process, mentioned by the process engineer, is the time it takes to execute the balancing process. The time spent re-balancing the assembly line depends on the main driving force behind re-balancing the assembly line: changes in takt time. When the takt time is changed, the assembly line needs to be re-balanced, because of the possibility that tasks no longer fit in a workstation's available time or a better allocation of tasks can be used. Logically, the time spent re-balancing is related to the change in takt time: a small change does not take much time to incorporate in the line balance, but a large change can result in a few days of re-balancing work for each worker position at a station, (J.L. Jiménez Sánchez, Project Engineer , personal communication, August 11, 2020; K. Svensson, Process Engineer, personal communication, September 10, 2020).

3 Literature review

This chapter provides the answer to the research question: "What is currently known about assembly line ergonomics and assembly line balancing problems?". First, we elaborate on assembly line ergonomics and the ergonomic assessment methods in Section 3.1. Next, we discuss the assembly line balancing problems (ALBPs) in Section 3.2: their general classification, which type of ALBP best fits Scania's case, and which methods are commonly used to solve such ALBPs.

3.1 Assembly line ergonomics

The objective of ergonomics is an important part of this research. Hence, we explore the definition of (assembly line) ergonomics in Section 3.1.1 and review different assessment methods in Section 3.1.2.

3.1.1 Definition

A general definition of the term 'ergonomics' can be found in the Cambridge Dictionary: "*the scientific study of people and their working conditions, especially done in order to improve effectiveness*" (Cambridge Dictionary, n.d.). While this is a good definition to start with, we explore the term further in academic literature. Koningsveld, Dul, Van Rhijn & Vink (2005) elaborate on the definition by including the social goals to protect the workers' health and the aspect of quality. Nunes & Cruz Machado (2007) describe that the discipline of ergonomics seeks to optimize the functioning of systems by diminishing or eliminating the incompatibility between workers and their work system.

Together, these definitions (and many more) suggest ergonomics and effectiveness are closely related, making it an important objective both for cost benefits as for humane benefits. Specifically, research has shown that work-related musculoskeletal disorders are common occupational diseases among assembly line workers due to repetitive motions or heavy workload (Botti, Mora, & Regattieri, 2017; Akyol & Baykasoğlu, 2019). Carnahan, Norman, & Redfern (2001) already described the potential physical overload of operators if an assembly line is balanced based solely on takt time. While the societal awareness of ergonomics has increased since then and developed countries are legislating workplace ergonomics, Akyol & Baykasoğlu (2019) state that "…, *it is barely considered in assembly line balancing literature*". Moreover, Mura & Dini (2019) state that assembly line balancing focused solely on economic factors will disregard potential indirect costs caused by worker health detriments. Unrelated to the specific process of balancing, many assessment methods have been developed to analyze (workplace) ergonomics.

3.1.2 Assessment methods

The ergonomic aspect of assembly processes is very important, especially when an assembly line relies on operators executing the large majority of the tasks (Mura & Dini, 2019). Some of the most popular assessment methods are the Quick Exposure Check (Li & Buckle, 1999), the method prescribed by the National Institute for Occupational Safety and Health (Waters, Putz-Anderson, & Carg, 1994), European Assembly Worksheet (Schaub, Caragnano, Britzke, & Bruder, 2010), Occupational Repetitive Action (OCRA) (Occhipinti, 1998) and Ovako Working posture Assessment System (OWAS) (Karhu, Kansi, & Kuorinka, 1977).

According to Lowe, Dempsey, & Jones (2019), the Rapid Upper Limb Assessment (RULA) ergonomic standard by McAtamney & Corlett (1993) was one of the most used in 2017. RULA is a survey method that is used in ergonomic assessments to prevent upper limb disorders. This method encodes the risk of injury due to physical exertion of the operator and provides a required level of action. The RULA assesses the posture of and forces on the neck, trunk and upper limbs, and the type of load and force (weight and intermittent/static). RULA yields a score ranging from 1 (acceptable ergonomics) to 7 (investigation and changes required immediately) (McAtamney & Corlett, 1993).

Lowe, Dempsey, & Jones (2019) point out that the Rapid Entire Body Assessment (REBA) (McAtamney & Hignett, 1995) is also one of the most used, and an extension of RULA. REBA elaborates on the RULA method by considering not only upper limbs but the entire body. While it is heavily based on RULA, some changes have been made. The REBA analysis identifies two groups: Group A considers the neck, trunk and legs, and Group B considers the upper arms, lower arms and wrists. The group scores are then combined to find the C-score. Finally, an activity score is added to this C-score to yield the final REBA score. We dive deeper into this assessment method and elaborate on the score composition of REBA in the coming paragraphs.

Neck

Movement	Score	Change score:
0°–20° flexion	1	+1 if twisting or side flexed
>20° flexion or in extension	2	

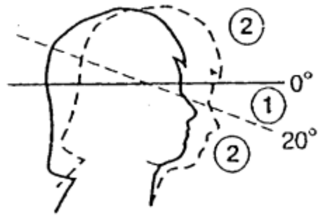

Figure 3-1. Illustration of Neck scoring method (Hignett & McAtamney, 2000)

Each body part within a group is scored separately, where a higher score indicates worse ergonomics. For Group A, the neck score (1 to 3) is based on the angle the neck makes compared to standing upright, and extra points are added if the neck is twisted and/or side bending (see Figure 3-1). The trunk score (1 to 5) is based on the movement and the angle that the trunk makes compared to standing upright. Similar to the neck score, extra points are added for a twisted or side bending truck position or movement. The legs are scored (1 to 4) according to whether both legs are weight bearing or only one, and extra points are added according to the angle of the knees (if the operator is not sitting down). The neck, trunk and legs scores are then combined using Table 3-1. A load/force score (0 to 3) dependent on the weight is then added to the combined score of Group A to yield Score A (Hignett & McAtamney, 2000).

Table 3-1. Table A of REBA (Hignett & McAtamney, 2000)

Table A	Neck											
	1				**2**				**3**			
Legs→ Trunk ↓	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
1	1	2	3	4	1	2	3	4	3	3	5	6
2	2	3	4	5	3	4	5	6	4	5	6	7
3	2	4	5	6	4	5	6	7	5	6	7	8
4	3	5	6	7	5	6	7	8	6	7	8	9
5	4	6	7	8	6	7	8	9	7	8	9	9

For Group B, the upper arms score (1 to 6) is defined by the angle of the arm compared to the position alongside the body. Extra points are added if the arm is abducted/rotated or if the shoulder is raised, but a point is deducted if the arm is supported. The lower arms score (1 to 2) is defined by the angle it makes to the upper arm. The wrists score (1 to 3) is defined by the angle it makes compared to the straight position and a point is added if the wrist is deviated or twisted. These scores are then combined using Table 3-2. A coupling score (0 to 3) is defined based on grip on a held object, whether it is easy to hold or not, and is added to the combined score to yield Score B (Hignett & McAtamney, 2000).

Table 3-2. Table B of REBA (Hignett & McAtamney, 2000)

Table B	Lower arm					
	1			**2**		
Wrist→ Upper arm ↓	**1**	**2**	**3**	**1**	**2**	**3**
1	1	2	2	1	2	3
2	1	2	3	2	3	4
3	3	4	5	4	5	5
4	4	5	5	5	6	7
5	6	7	8	7	8	8
6	7	8	8	8	9	9

Finally, Score A (1 to 12) and Score B (1 to 12) are combined to find Score C, using Table 3-3. The next score to be determined is the activity score (0 to 3), which consists of points which are added when the action is either static for longer than 1 minute, repeated more than 4 times per minute or if the action causes rapid large changes in postures. This score added up to Score C yields the REBA score (1 to 15). A REBA score of 1 indicates no further action is necessary, scores of 2 or 3 indicate a low risk level, 4-7 indicates medium risk, 8-10 indicates a high risk and 11-15 indicates a very high risk. These risk levels indicate the probability of developing work-related musculoskeletal disorders (Hignett & McAtamney, 2000).

Table 3-3. Table C of REBA

Table C		Score B											
		1	2	3	4	5	6	7	8	9	10	11	12
Score A	1	1	1	1	2	3	3	4	5	6	7	7	7
	2	1	2	2	3	4	4	5	6	6	7	7	8
	3	2	3	3	3	4	5	6	7	7	8	8	8
	4	3	4	4	4	5	6	7	8	8	9	9	9
	5	4	4	4	5	6	7	8	8	9	9	9	9
	6	6	6	6	7	8	8	9	9	10	10	10	10
	7	7	7	7	8	9	9	9	10	10	11	11	11
	8	8	8	8	8	9	10	10	10	10	11	11	11
	9	9	9	9	10	10	10	11	11	11	12	12	12
	10	10	10	10	11	11	11	11	12	12	12	12	12
	11	11	11	11	11	12	12	12	12	12	12	12	12
	12	12	12	12	12	12	12	12	12	12	12	12	12

REBA and other assessment methods are further discussed when touching upon the different types of assembly line balancing problems in Section 3.2.1.

3.2 Assembly line balancing problems

Assembly line balancing problems are widely discussed in literature. First, we elaborate on assembly line balancing problem classification in Section 3.2.1. Next, we classify Scania's problem according to the reviewed literature in Section 3.2.2. Finally, we explore suitable solution methods for Scania's case in Section 3.2.3.

3.2.1 Assembly line balancing problem classification

According to Fathi et al. (2018, p. 456), assembly line balancing problems (ALBPs) can be categorised into two main groups based on the problem's assumptions and limitations: simple ALBPs (SALBPs), and generalised ALBPs (GALBPs). Fathi et al. (2019, p. 32537) also describe this classification and specify the SALBPs as making simplifying assumptions, whereas the GALBPs are described to deal with real-world constraints and practical considerations. Moreover, they describe a classification considering the number of different models assembled on the assembly line: single-model or mixed-model ALBPs (MMALBPs). Another classification according to literature (Fathi et al., 2018; Manavizadehet al., 2012), is concerned with the objective: a type I ALBP minimises the number of workstations given the cycle time, a type II ALBP minimises the cycle time with a given number of workstations. Moreover, type E indicates the minimisation of both and type F has all parameters fixed and merely checks feasibility (Fathi M. , Nourmohammadi, Ng, & Syberfeldt, 2020). Table 3-4 provides an overview of these general classifications.

Table 3-4. Overview of ALBP classifications

Aspect	Options	Sources
Assumptions	Simple	(Fathi, Moris, Ghobakhloo, & Fontes, 2018) (Fathi, Nourmohammadi, Ng, & Syberfeldt, 2019)
	Generalised	
Number of models	Single model	(Fathi, Nourmohammadi, Ng, & Syberfeldt, 2019)
	Mixed model	
Objective	Minimise number of workstations (Type I)	(Manavizadeh, Rabbani, Moshtaghi, & Jolai, 2012) (Fathi, Moris, Ghobakhloo, & Fontes, 2018) (Fathi M. , Nourmohammadi, Ng, & Syberfeldt, 2020)
	Minimise cycle time (Type II)	
	Minimise both (Type E)	
	Test feasibility (Type F)	

Other types of ALBPs mentioned in literature include the types of constraints. Fathi et al. (2019, p. 32538) mention the zoning constraints: activities that should be placed in the same workstation (or in close proximity) are considered in positive zoning constraints (PZCs) while negative zoning constraints (NZCs) indicate combinations of activities that must not. These constraints are formulated according to the safety skill and equipment requirements of the activities (Yuan, Zhang, & Shao, 2015). Besides the zoning constraints, Yuan et al. (2015, p. 160) mention positioning constraints: constraints that assign an activity to a workstation based on facility layout, such as higher ceilings in a certain area or unmovable tools.

Another consideration is the type of demand for the line. A constant production yields a deterministic demand-type, whereas uncertainty in demand levels yields a stochastic demand that must be considered in the balancing process (Bukchin, Dar-El, & Rubinovitz, 2002). Stochasticity also occurs on activity-level; workers' skills or condition or other environmental factors can influence the task times of activities (Fathi, Nourmohammadi, Ng, & Syberfeldt, 2019).

Finally, the layout of the assembly line influences the type of ALBP. According to Nilakantan et al. (2016, p. 232), a straight assembly line is the more traditional form, while the U-shaped assembly line is described to be more flexible and provides better productivity, since one operator could execute tasks at multiple stations. Fathi et al. (2018, p. 457) provide a schematic view of these two shapes, which increases the understanding of productivity advantages, see Figure 3-2.

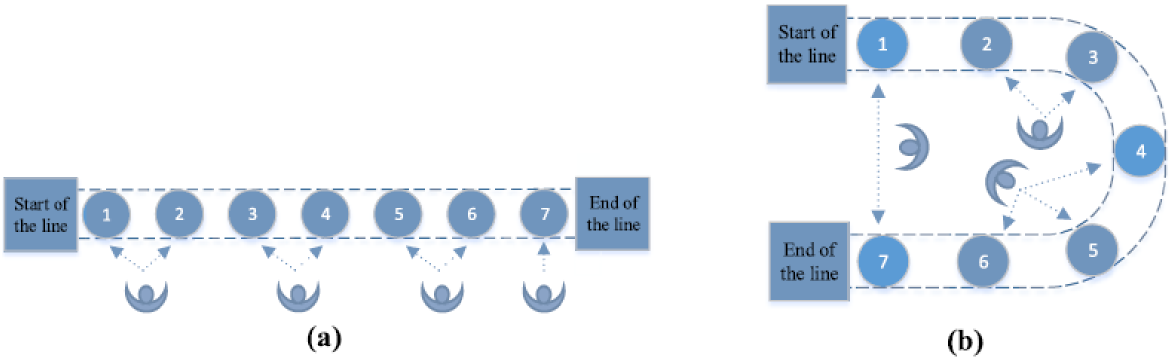

Figure 3-2. Assembly line configurations: (a) straight and (b) U-shaped (Fathi, Fontes, Moris, & Ghobakhloo, 2018)

Ergonomics in ALBPs

Several researchers have also explored the inclusion of ergonomics into the assembly line balancing. To better accommodate the goal of including ergonomics into the balancing process, we specify our search into ALBPs that include the ergonomics aspects. In our research, we encountered Alghazi & Kurz (2018) including the ergonomics aspect in the shape of a constraint: the total weighted ergonomic risk score of all tasks cannot exceed a predefined threshold. However, we found most research was done into the inclusion of ergonomics into the objective of an ALBP, aiming to minimize the ergonomic risks.

The ergonomic objectives found in literature are based on two categories of calculations: 'energy expenditure/fatigue' and 'assessment methods'. We first describe the existing literature concerning the first category. Kara et al. (2014) employ a single-objective ALBP that aims to minimise overall costs and simultaneously incorporates both physical strain (energy expenditure) and psychological strain (task rigidity). Considering a walking worker assembly line (WWAL), Al-Zuheri et al. (2016) develop a multi-objective model that includes minimising energy consumption as one of the objectives. Battini et al. (2016) propose a multi-objective SALBP: minimizing cycle time and also energy expenditure, the last of which is based on their own Predetermined Motion Energy System to quickly estimate the consumed energy (Battini D. , Delorme, Dolgui, Persona, & Sgarbossa, 2016). Mura & Dini (2019) include specific workers' skill levels and physical abilities in their energy expenditure objective calculations, next to the objective of minimising the number of workstations.

Besides the energy expedition, other measures of fatigue are also mentioned in literature. Carnahan et al. (2001) already used grip strength as an indicator of fatigue. Battini et al. (2015) compared two methods in their paper: the energy expenditure method and the rest allowances method. Another measure is introduced by Abdous et al. (2018), who consider ergonomics in their multi-objective SALBP by calculating muscle fatigue. Finco et al. (2020) continue on Battini's topic and introduce the rest allowance into an SALBP-II that minimizes the smoothness index.

The second category contains literature concerning ergonomic objectives based on assessment methods' calculations. Cheshmehgaz et al. (2012) incorporate a simplified version of OWAS to examine posture diversity and optimize the physical workload and CT simultaneously. Di Benedetto & Fanti (2012) promote the use of OCRA, through a line balancing and ergonomics assessment tool called ErgoAnalysis. Barathwaj et al. (2015) describe using the RULA assessment method to calculate the Accumulated Risk Posture. This parameter is minimized, next to the number or workstations, for an MMALBP using a genetic algorithm (GA). Akyol & Baykasoğlu (2019) introduce ergonomics in an ALBP variation called assembly line worker assignment balancing problem (ALWABP) and also use the OCRA assessment method to minimize the ergonomic risks next to minimizing the CT. Finally, Polat et al.

(2018) employ the REBA assessment method to assess workload of operations. They combine the ergonomics and the cycle time into one objective and solve using Goal programming.

Table 3-5. Ergonomic objectives in ALBPs literature overview (GA = Genetic Algorithm, MRH = Multiple Ranking heuristic)

	ALBP Type				Objective							Constraints				Solution approach				
					Regular				Ergonomic											
Literature	SALBP	GALBP	MMALBP	Other	CT	Nr of Work-stations	Smoothness index	Costs	Energy expenditure	Fatigue	Assessment method	Precedence	Zoning	Worker skills/ abilities	Resources	Mathematical programming	Heuristic	Meta-heuristic	Other	**User case**
Kara et al. (2014)		X						X	X			X		X	X	X				
Al-Zuheri et al. (2016)			X	WWAL				X	X			X		X				GA		
Battini et al. (2016)	X				X				X			X				X				X
Mura & Dini (2019)	X					X			X					X				GA		X
Carnahan et al. (2001)	X				X					X		X		X				MRH & GA		
Battini et al. (2015)	X				X				X	X		X				X				X
Finco et al. (2020)	X						X			X		X			X		X			
Abdous et al. (2018)	X					X				X		X				X				
Akyol & Baykasoğlu (2019)				ALWABP	X						OCRA	X					X			
Di Benedetto & Fanti (2012)				-							OCRA								Manual	
Cheshmehgaz et al. (2012)	X				X						OWAS	X						GA	Fuzzy Goal Programming	
Barathwaj et al. (2015)			X			X					RULA	X						GA		
Polat et al. (2018)	X				X						REBA	X				X			Goal Programming	
This project		X	X		X						REBA	X	X			X		GA		X

In conclusion, these studies indicate that research has been done concerning incorporating ergonomics into ALBPS (see Table 3-5), but there is no consensus on which method is best to employ. The energy expenditure methods are often reported to be preferable for being computationally simple (Battini D. et al., 2015). However, while the assessment methods require more time to gather the data, these methods are reported to be more often used in practice (Battini D. et al., 2016; Otto & Scholl, 2011). We need to compare the literature to Scania's case to be able to make a decision.

3.2.2 Scania's assembly line balancing problem

Scania's process to be balanced is an assembly line, which fits the term of assembly line balancing problems. Based on the process described in Section 2.1, we compare Scania's case to the ALBP classification used in literature as described in Section 3.2.

Since Scania's case includes many practical considerations and real-world constraints, it is theoretically classified as a generalised ALBP. Moreover, the assembly line is able to produce all combinations of modular choices the customer can make; the mixed-model ALBP (MMALBP) is thus suitable for Scania's case. In terms of objective classification, the current objective is productivity, which fits best with the type II category. However, the desired balancing approach includes two objectives. Thus, Scania's ALB case is best compared to literature concerning generalised MMALBPs of type II, with the addition of a second ergonomic objective.

In terms of including the ergonomics aspect into the ALBP, Scania employs their own specific assessment method, Scania Ergonomic Standard (SES), but this is corporate information and cannot be shared. To do this research without using SES, we explored the other assessment methods and we found REBA most suitable for three reasons. First, REBA is one of the most used posture assessment methods by ergonomists, according to Lowe et al. (2019). Second, to Scania it is a well-known and trusted method that assesses the entire body posture and is somewhat comparable to SES. While SES is more elaborate, both methods include the important aspects of full body postures and joint angles in their assessment. Third, the literature review shows very little research has been done into the incorporation of REBA assessed ergonomic risks in ALBPs. Polat et al. (2018) conducted their experiments with a randomly generated workload and recommend the use of a case study to explore this promising option. Hence, choosing REBA and applying it on an MMALBP case study would bridge the current knowledge gap.

3.2.3 Suitable methods

Considering single model ALBP-I with both straight and U-shaped configurations, Fathi et al. (2019, p. 32539) show mathematical programming, exact algorithms, heuristics and meta-heuristics have all been used to find a solution. Meta-heuristics are very common, for example, genetic algorithms and simulated annealing methods as used by Baykasoğlu & Özbakır (2007) and Cakir et al. (2011) respectively. Recently, Nourmohammadi et al. (2019, p. 129824) described using a novel meta-heuristic method the water flow-like algorithm, for solving a U-shaped ALBP-I.

Focussing on MMALBP solution approaches, we find Thomopoulos (1967) assessed an MMALBP using a modified heuristic approach used in single model ALBPs. Bukchin et al. (2002) used a heuristic including a branch and bound method to solve its MMALBP-I with stochastic demand. Manavizadeh et al. (2012, p. 12027) assessed an MMALBP with stochastic demand and both objective types I and II simultaneously. They also used a meta-heuristic, namely a multi-objective genetic algorithm, as they found it was the best of six assessed types of multi-objective evolutionary algorithms.

The MMALBP problem is found to be Non-deterministic Polynomial-time (NP) hard (Bukchin, Dar-El, & Rubinovitz, 2002), so mathematical programming and exact algorithms are less suitable for larger cases. While these methods may work on the pedal car test case, which has a limited number of tasks and stations, they are unlikely to be successful in the actual truck assembly line balancing process. However, first solving the problem using mathematical programming (using a predefined time limit), can give an indication of a possibly optimal solution. Nevertheless, meta-heuristics are the best options for larger cases, since those might find an optimal solution in reasonable time. The literature found considering ALBPs with ergonomic objectives also takes this approach: small cases are solved with mathematical programming and larger ones with meta-heuristics.

4 Approaches

This chapter answers the research question: "Which approaches can improve Scania's assembly line balancing process?". Initially, we describe the approaches in general and how they relate to each other. Next, we describe the data gathering process in Section 4.1. We elaborate on the first approach, combining the two balancing objectives productivity and ergonomics into the manual assembly line balancing process, in Section 4.2. We describe the second approach of automating the process in Section 4.3, where we distinguish between an exact method and a meta-heuristic.

To start including the aspect of ergonomics in the balancing process of Scania's case, we take a preparation step and evaluate two approaches. The preparation step consists of gathering the ergonomic data. While the tasks and task times are available and currently used in the balancing process, the ergonomic data is not. The ergonomic data gathered in the preparation step is used as input in the two approaches: manual and automated balancing. The first approach includes the ergonomics objective but remains manual, as in the current situation. In the second approach, we optimize the process by automation: we use operations research techniques to solve Scania's assembly line balancing problem to (near) optimality. Figure 4-1 provides an overview of the sections of this chapter and the flow of actions inside these sections.

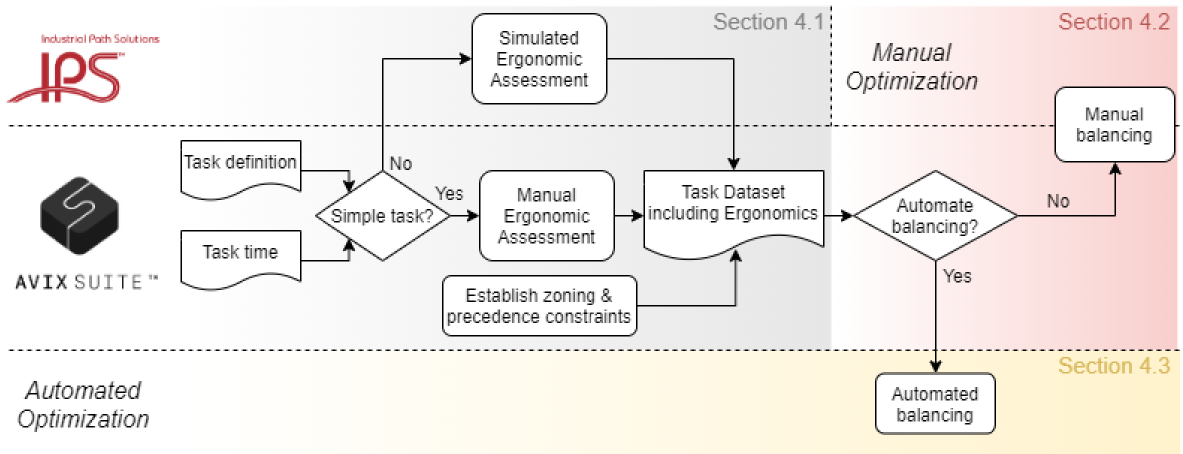

Figure 4-1. Chapter overview

In this project, we use the Pedal Car Test Case (PCTC) as a basis, the reasons for which are described in Section 1.2. For this PCTC, the assumptions are defined as follows:

- The number of workstations is fixed. In practice, the assembly line is not re-arranged often, but the target of produced trucks per day does vary. In consultation with Scania, we made the decision to focus this research on the re-balancing activities, which do not involve changing the layout of the assembly line and thus, have a fixed number of workstations.
- Task time is fixed and equal for all operators. The task times are based on Scania Time Blocks, a time measurement method that is specific to Scania and proven satisfactory. Since the time measurement method is outside of the scope of this project, we assume it is fixed and a good representation of reality.
- In the PCTC we aim to assign tasks to stations, but not to operators on that station. In Scania's assembly process, multiple operators are working at each workstation. However, for model simplicity, we now consider the station to have just one operator. To apply this model in practice, however, a second step would need to be taken to assign tasks within stations to its multiple operators.

- The two models of pedal cars (black/red) must be assembled on the same assembly line and the tasks are assigned to a station independently from the variants. For example, if the steering wheel is mounted in station 2, this is done in station 2 for both models.
- The balance must work for both models, they are not weighted based on frequency. The CT of a balance equals the highest workload of all models on all stations, same for ergonomic measures.
- The performance of the balance is defined by three KPIs: cycle time (CT), the sum of all stations' ergonomic risk scores (SUM) and the maximum value of all stations' ergonomic risk scores (MAX). All three KPI's are to be minimized for optimal productivity and ergonomics. The two ergonomic risk KPI's will not be assessed simultaneously. We elaborate on these decisions in Section 5.1.

These case assumptions are equal for all approaches.

4.1 Data gathering

We describe the data gathering in two parts: ergonomic data gathering and establishing the zoning and precedence constraints.

4.1.1 Ergonomic data gathering

One of the core problems of this research indicates that currently the ergonomics aspect is not incorporated in balancing because of the time it takes to execute ergonomics assessments. Using simulated ergonomics assessments would solve this time issue. Scania's current process includes the use of the AviX software, but not the (regular) use of the available program Industrial Path Solutions (IPS), which contains the digital human modeling tool Intelligently Moving Manikins (IMMA). We refer to the ergonomic assessment tool IPS-IMMA as IMMA for short. This tool is used for creating simulations of human motions which can then be objectively assessed. Hanson, Högberg and Söderholm (2012) assess this tool to be promising for executing ergonomic assessments and Scania is familiar with its use. Thus, we specify the preparation step to incorporate the use of a connection between AviX and IMMA software programs when gathering the ergonomic data.

We explore this connection in close contact with the MOSIM project and the developers of AviX and IMMA. The MOSIM project has a bi-weekly meeting to discuss the general progress of the connection and the other team members' activities. To yield a satisfactory result for Scania, we act as a test user of the AviX-IMMA connection. We organized a weekly meeting with one developer from AviX and one from IMMA to discuss how we experience the intermediate releases of the connection, and what can be improved.

The combination of the time and ergonomics objectives would ideally be incorporated in one single software program, which the process engineers manually use to find a good balance. Currently, the process engineers use AviX to balance the assembly line. Hence, we attempt to achieve a connection between the two software programs so that ergonomic assessment results can be viewed in AviX. To do this, the information from the tasks and sequences in the AviX program will need to be analyzed in IMMA to yield ergonomic scores, which are shown in the AviX software. A full incorporation of the two software programs is not attempted, but the developers have created an integration with the functionality to easily export the tasks' data from AviX, import it to IMMA to simulate and ergonomically assess them in IMMA and export/import back from IMMA to AviX. We elaborate on each step of this general process (see Figure 4-2) in the next paragraphs.

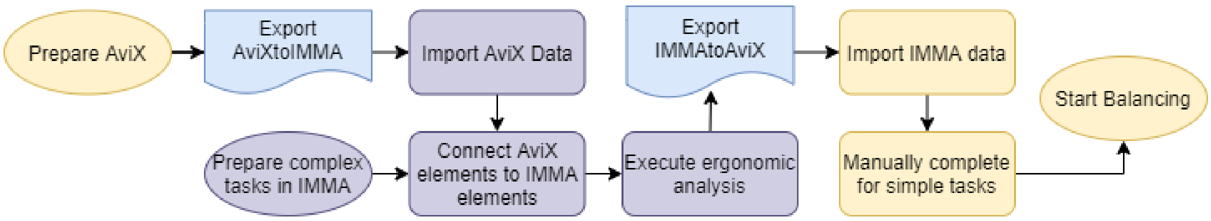

Figure 4-2. Flow chart of Manual objective combination approach

Prepare AviX

To perform the ergonomic analysis of the tasks in AviX, first the source file in AviX needs to be complete with all the tasks. In AviX, the tasks are displayed in the method tree, with the hierarchical levels of factory, building, line, workstation, (human) resource, machine resource, process group and task (see Figure 4-3). At the lowest level, a task can contain several types of analyses for time estimation. Besides the time component, each task can be assigned tools and parts that are used. To illustrate the tools and parts used, images can be added in AviX. To these images, grip or attach marker indicators can be added to show the interaction of the part/tools with the manikin or with each other. Finally, the tasks can be exported to IMMA for simulated ergonomic risk assessment.

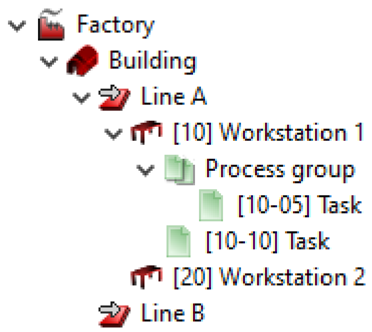

Figure 4-3. AviX Method Tree Hierarchy

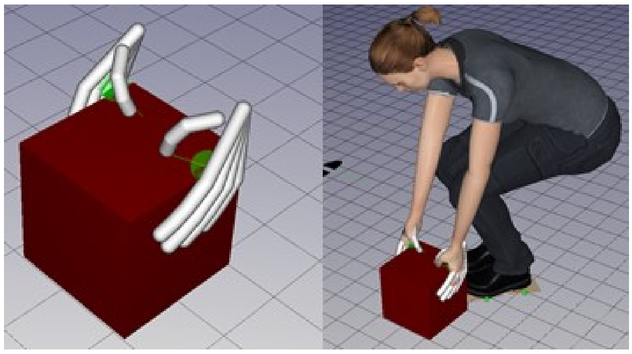

Figure 4-4. Grip points on box (left) and in use (right)

Prepare IMMA

The next step in preparation concerns the IMMA tool. The tasks that are to be assessed in IMMA need to be recreated in the IMMA environment. This includes importing the objects (in IMMA: geometries) of the environment (also called the 'scene'), parts and tools, and creating collision-free paths for assembly. In these simulations, the operator is represented by so-called manikins. These manikins are created in IMMA and can be altered to a wide range of sizes, body types and are available in both male and female versions. In this case, we use the standard manikin supplied by the IMMA software. This standard (female) manikin's body measurements are based on the 50th percentile female anthropometrics in Sweden, according to research conducted by Hanson et al. (2009). The objects that are held by the manikin are provided with 'grip points': hand shapes that represent where the manikin's hands go when interacting with the object, see Figure 4-4.

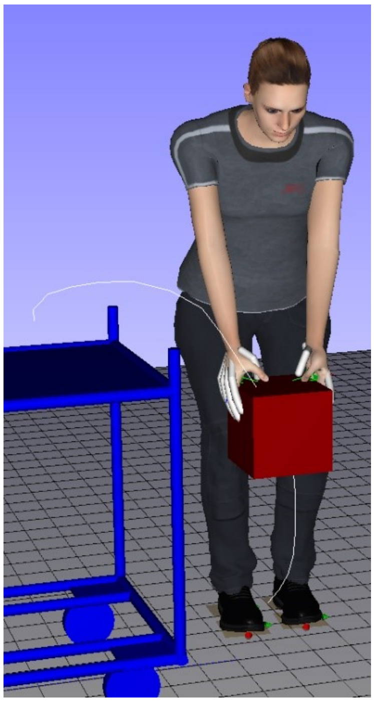

Figure 4-5. Collision-free path from floor to cart (white line)

For each task, the movements are modelled by creating an operation sequence in IMMA: a sequence of events that have been prepared. The operation sequence consists of so-called 'actors' performing activities. These 'actors' include all the moving elements in a task. For example, if the task of an operator is putting a box on a cart, both the operator and the box are actors in the process sequence. These actors get assigned activities; in the same example, the operator needs to grasp the box and release it again, while the box' activity is to follow a pre-defined (and collision-free) path onto the table, see Figure 4-5. These activities are also assigned a sequential order: the box moves between being grasped and being released by the operator. The example process sequence is depicted in Figure 4-6.

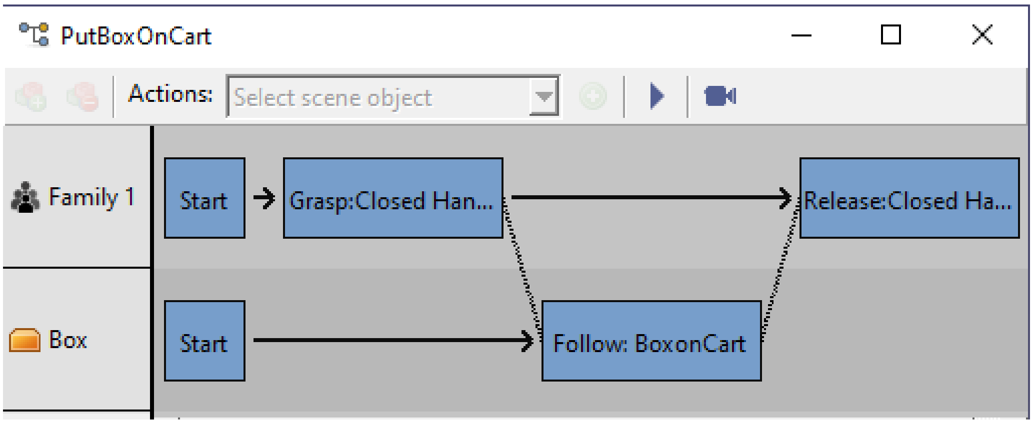

Figure 4-6. IMMA operation sequence of an operator putting a box on a cart

While ergonomic risks need to be assessed for all tasks, the process of simulating the task requires knowledge of the software program IMMA and time to do the preparation described above. Hence, in consultation with the ergonomics specialist of the Smart Factory Lab (L. Hanson, SFL team leader, personal communication, December 16, 2020), we decide to distinguish between simple and complex tasks; only the last of which are simulated using IMMA. This distinction would be made in practice by the process engineer or ergonomist, based on the possibility to assess the entire task by filling in the REBA form manually. If there are too many different body postures in a task or if the postures are unusual, this is seen as complex. In this project, the tasks that include simply walking or fetching light tools/parts are considered simple, all others are complex.

Import AviX data to IMMA & connect elements

After the preparations in both AviX and IMMA are complete, the AviX export file can be imported to IMMA. This prompts an 'AviX Wizard', a graphical user interface that makes it easier to connect the imported tasks (called 'Blocks' in IMMA), with the prepared parts, tools and operation sequences, see Figure 4-7. If the tools and parts contain grip-markers, the grip points in IMMA are connected to them. After these connections have been made, the next step is to evaluate the ergonomics.

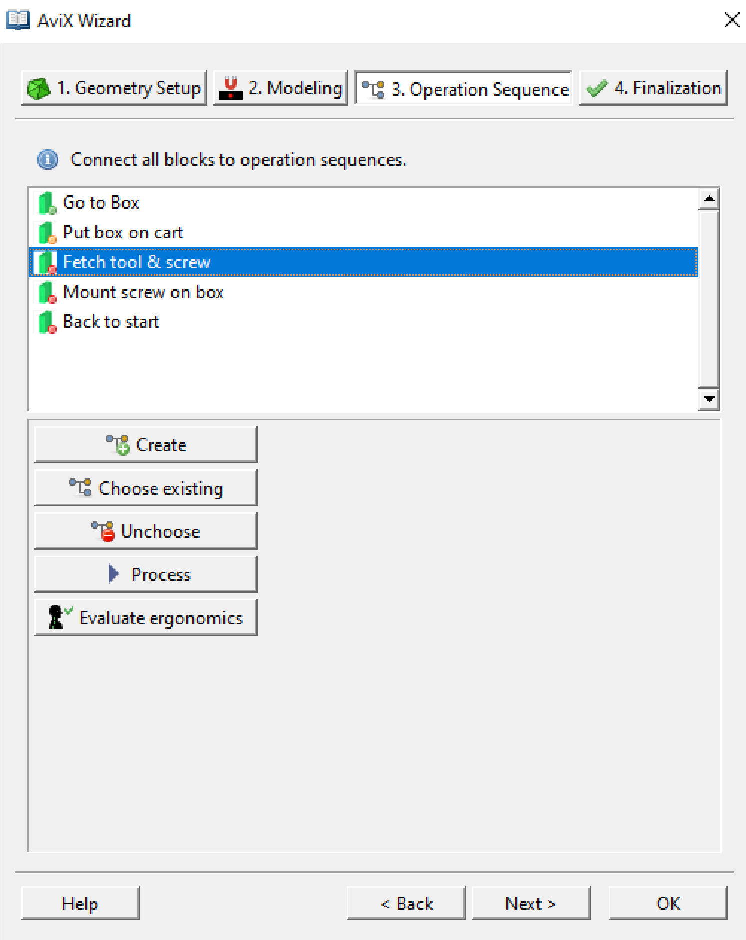

Figure 4-7. AviX Wizard in IMMA

Execute ergonomic analyses

When all AviX' parts, tools and tasks are linked to IMMA simulations, the tasks can be ergonomically evaluated. This ergonomics assessment is done based on the REBA assessment method, the choice for which can be found in Section 3.2.2. This ergonomic analysis starts when the wizard is finished. As explained in Section 3.1.2, the REBA assessment method is based on a body part's posture score and a change score: the posture score is defined by joint angles and the change score varies per body part; an example is that the trunk or neck is also twisted, or that the shoulder is raised. The posture score is found by IMMA automatically. However, some of the change scores are not; the wizard gives the option to answer questions that provide the necessary information to calculate the change scores, see Figure 4-8. If this option is not chosen, the export file shows that no questions have been answered and leaves the change score to the manual completion phase. The results of the ergonomic analysis are shown in IMMA, as shown in Figure 4-9.

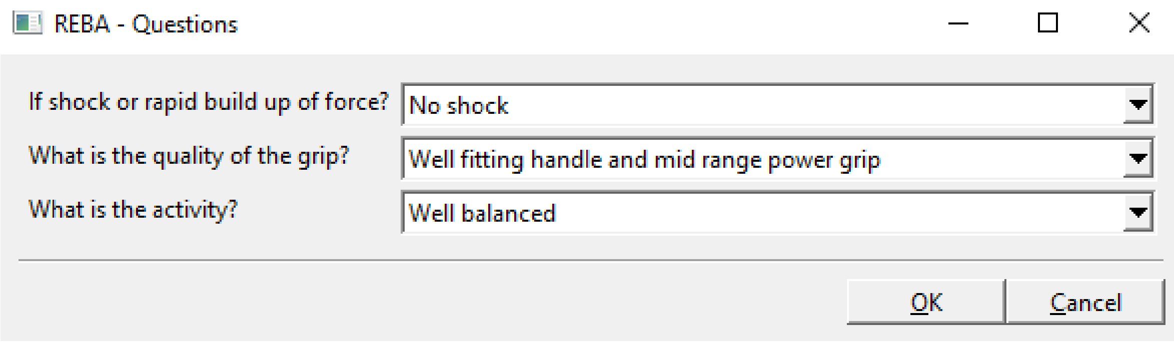

Figure 4-8. REBA Questions in IMMA

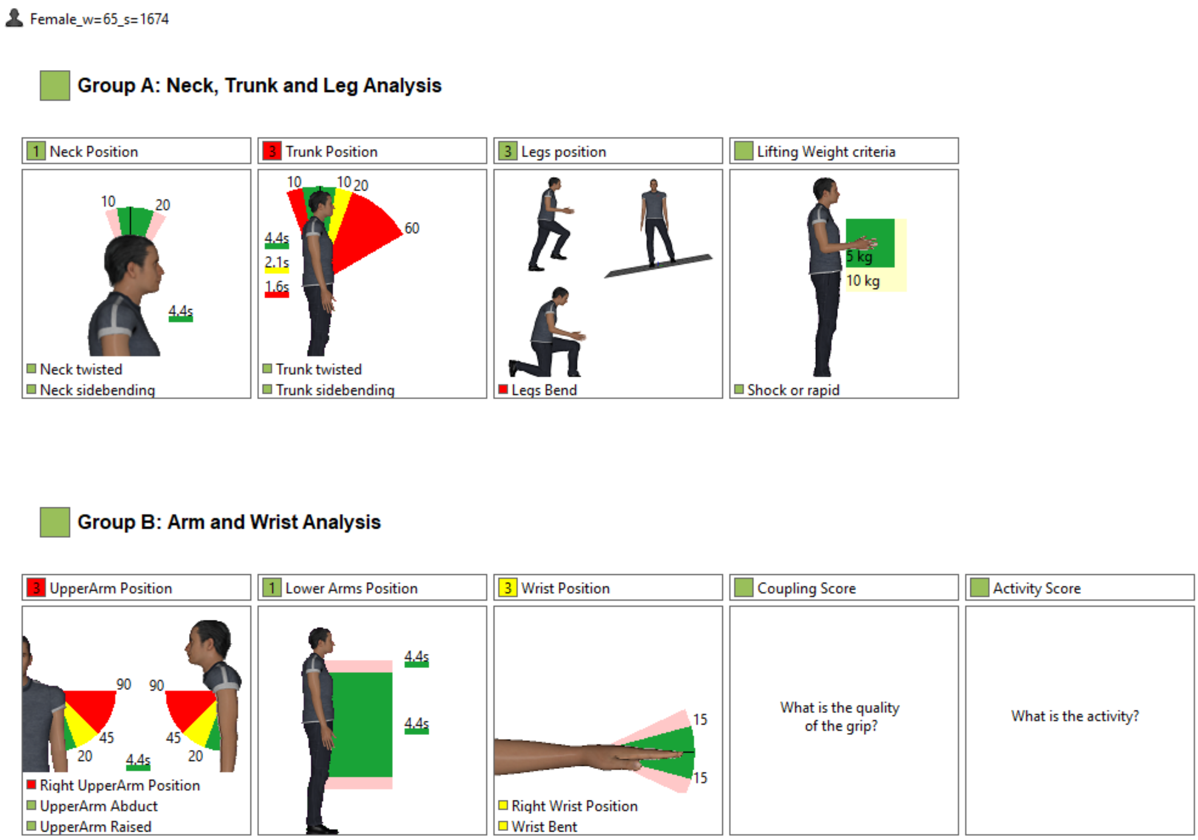

Figure 4-9. IMMA REBA report

Import IMMA data to AviX & manually complete ergonomic data

After finishing the wizard and all the ergonomic assessments, we export the data and import it back into AviX. There, each task that has been assessed in IMMA now has a REBA score attached. To complete the ergonomic scores in AviX, the simple tasks are assessed manually by filling in the REBA sheet, see Figure 4-10. Furthermore, the complex tasks that have an incomplete REBA sheet (due to not answering the questions in the IMMA wizard), are manually completed in this same sheet.

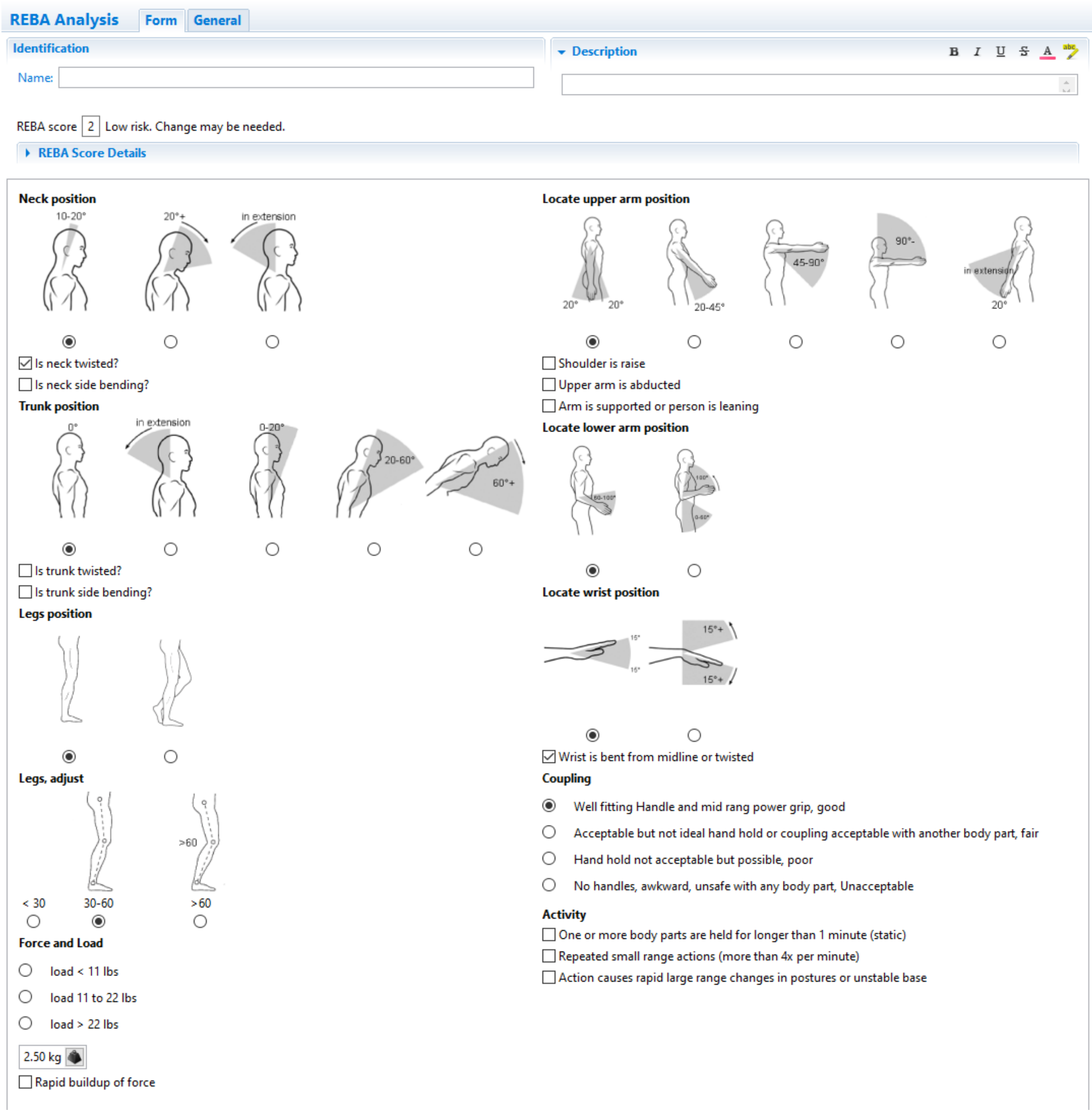

Figure 4-10. REBA sheet in AviX

When a task is fully assessed, i.e. the REBA sheet has been filled in, it indicates the final REBA score (above the sheet). AviX also provides the user with a graphic to illustrate the posture's scores. When a balancing activity is started, the user can also open this graphical representation in the Balance section of the AviX software, where a balance chart is shown, see Figure 4-11. This shows the representation of the ergonomic scores in AviX, when selecting an entire station. The ergonomic result window shows the time-weighted average REBA (TWAR) score of the task/station/line selected. Moreover, it shows the separate tasks with their REBA scores and task times. This way, the process engineer can see which task might have a bigger influence on the station's TWAR.

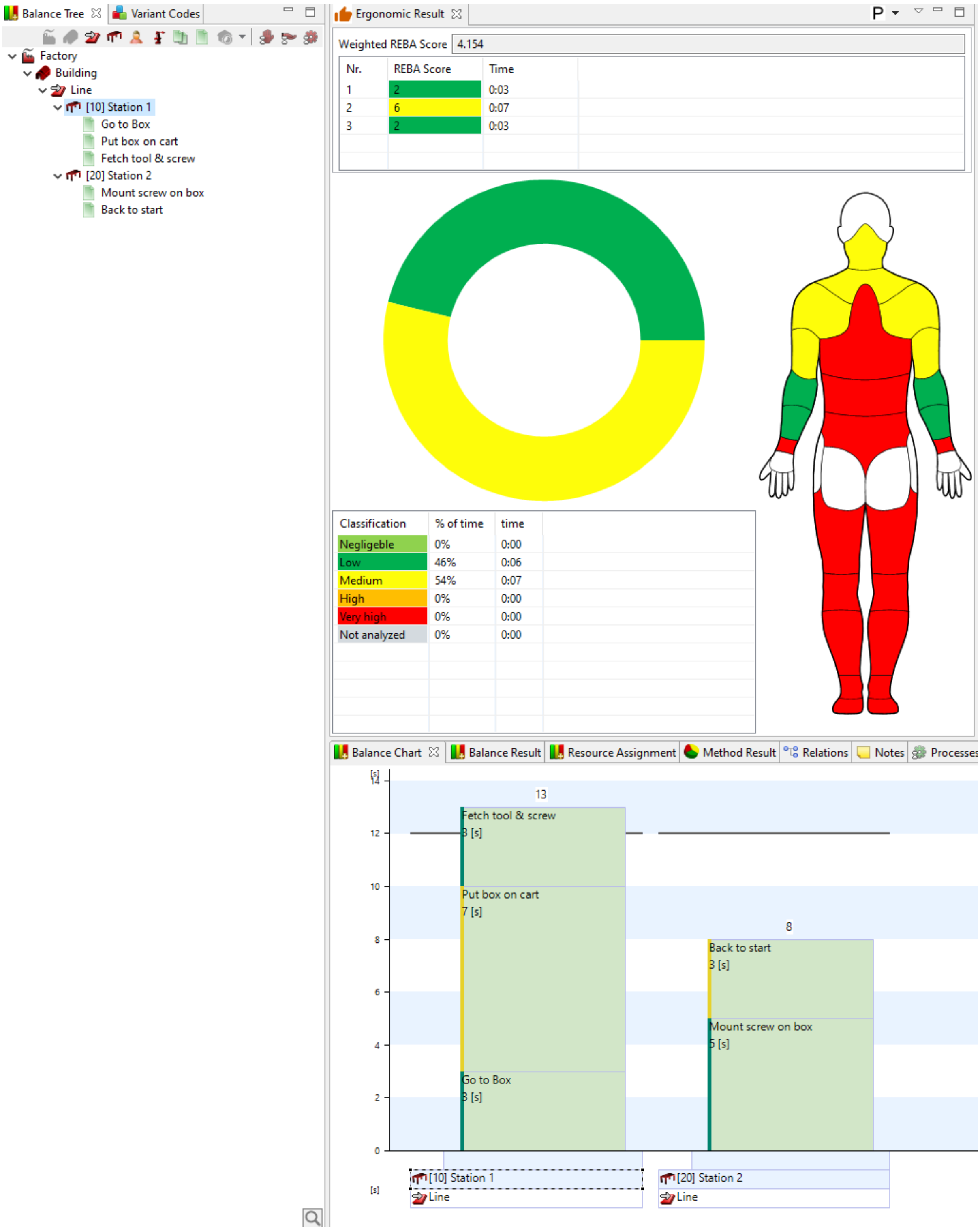

Figure 4-11. AviX Balance module including Ergonomics

4.1.2 Establish precedence and zoning constraints

Finally, the assembly process needs to adhere to certain constraints. In this case, we consider two types: precedence and zoning constraints. The precedence constraints that are present in the final assembly process of Scania trucks are approximately defined in the SAMS file, as mentioned in Section 2.1. However, the task-level precedence constraints are not; the process engineers rely on input from assembly line operators. Since this research is focused on the balancing process itself, the precedence relations need to be provided for the PCTC. These relations are determined by examining the assembly process and assessing which sequence of tasks is obligatory. For example, the wheel cannot be tightened before it is mounted. Such relations between tasks are displayed in a precedence graph, see Figure 4-12.

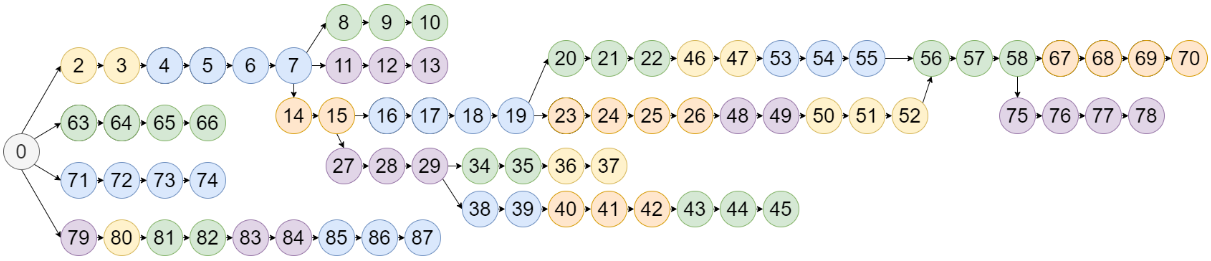

Figure 4-12. Precedence diagram of PCTC tasks

We determine the zoning constraints in a similar fashion; examining the process and defining which tasks cannot be divided over multiple stations. For example, fetching the wheel from storage and mounting it cannot be divided over separate stations. The zones are indicated by the colours: adjacent tasks with the same colour belong to one zone. In Figure 4-12, tasks 4, 5, 6 and 7 form one zone, tasks 16, 17, 18 and 19 form another zone.

4.2 Manual approach

The current process, described in Section 2.2, is manual and does not include an ergonomic aspect. Hence, the first approach is to still employ a manual balancing process, but to include simulated ergonomics assessments into the manual balancing process. Thus, we specify the first approach to use the connection between AviX and IMMA software to gather the ergonomic data for executing the balancing process. This process still is manual but will ensure the incorporation of the ergonomic aspect during the balancing, instead of assessing the ergonomics in hindsight.

This approach encompasses a process engineer manually balancing the assembly line, as is the case in the current situation (see Chapter 2). The addition to the current method, however, is the incorporation of the ergonomic aspect. As discussed, the connection between AviX and IMMA enables the process engineer to assess the ergonomic consequences of putting certain tasks together in a station. To examine the effects of having this information, we conduct experiments with process engineers. The experiments consist of two parts: A) the current way of working, B) including ergonomics. The aim of these experiments is to gauge the feasibility of the new manual balancing process, and how much value it adds to include ergonomics to the current process in terms of ergonomic improvements. The experiments require participants that have experience in workload balancing, and preferably also experience with doing so in AviX. The suitability of participants is registered by having them fill in a questionnaire before the experiments, which allows them to describe their level of expertise and their experience (see appendix A). All participants perform all experiments sequentially, an overview of which is shown in Figure 4-14.

The participants are provided with a short introduction meeting describing the aims, the required AviX package and the data: an AviX file and precedence diagram. Since the current process requires input from the assembly line operators for defining precedence relations, we choose to now provide the precedence diagram. Since the participants can only move zones in their entirety from one station to another, the tasks are grouped into their zones and given zone numbers. The precedence diagram provided to the participants is thus the diagram containing the zones precedence, as shown in Figure 4-13. In this figure, the colors of the zones in Figure 4-12 are kept to show the link between the task-level and zone-level precedence graph.

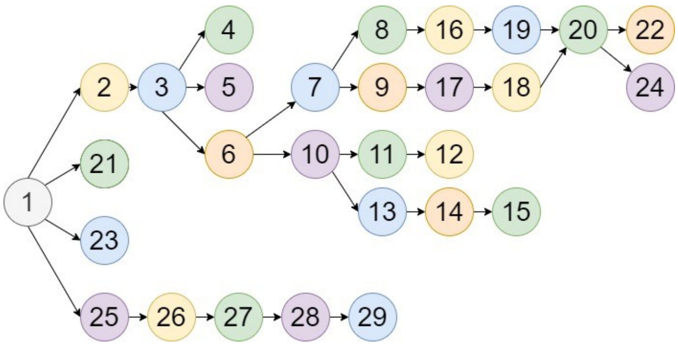

Figure 4-13. Precedence diagram of PCTC zones

The AviX file that we provide to the participants has two versions: one without and one with ergonomic data. Besides the ergonomics data, these files are equal. They contain one prepared factory, building and line (as shown before in Figure 4-3), under which the number of expected stations is prepared. All the tasks are initially found under the first station grouped in their zones. It is then up to the participants to drag and drop these zones from one station to another, taking into account the precedence relations and their objectives. The participants are given deadlines for the experiments. These deadlines are aimed at allowing the participants to participate alongside their normal workload and to ensure we receive the results in a timely manner.

For experiment A1, the participants are aiming for the best possible balance (in reasonable time) and are provided with the AviX file without ergonomic data. After completing experiment A1, the users are provided with some ergonomic feedback. This feedback is based on the ergonomic data that the participants will also receive in Experiment B. As per the current situation, the feedback does not specify which tasks are specifically causing worse ergonomics in a station. The feedback merely points out which station performs worst in terms of ergonomic risks. The participants are then instructed to try and include this feedback for the completion of experiment A2.

When the first experiment is finished, the participants receive the AviX dataset with ergonomic data. They are then instructed to aim for the best balance possible (in reasonable time), when including the objective of minimal ergonomic risks. They can now see the effect of adding a zone of tasks to a station and can keep track of the stations' time-weighted average REBA score. Finally, after completing the experiment, the participants fill in a second questionnaire (see Appendix A) to describe their experiences. The results of the experiments are described in Section 5.2.2. We now elaborate on the automated balancing options.

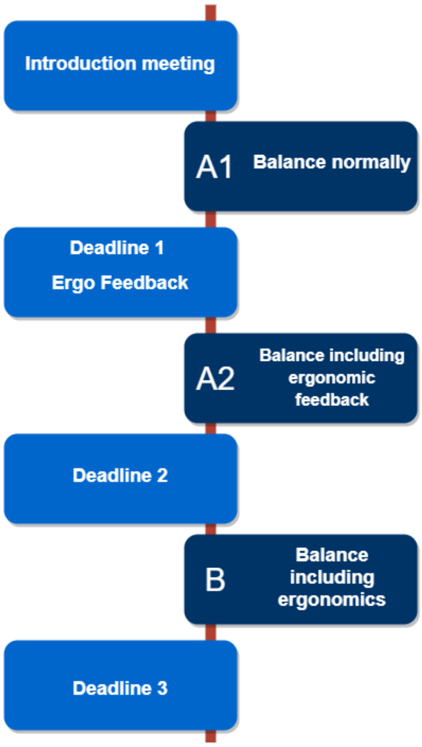

Figure 4-14. Overview Experiments

4.3 Automated approach

Another solution to improve the balancing process is to automate; creating a suitable method and receiving a (near) optimal solution from it. Currently, the balancing process is manual and is based on the process engineer's experience and input from the operators on the assembly line. However, this process is based on the aim to make the balance feasible in practice and for each station to have a WACT of 90%-100% of the takt time. Therefore, this is not an optimised process: the process engineers stop balancing when these aims are satisfied and do not use computational tools to explore the possibilities for improving the productivity and ergonomics. By automating this process, we achieve a wider solution space by exploring options that otherwise might have been skipped. However, since the MMALBP is NP-hard (Bukchin et al., 2002; Manavizadeh et al., 2012), an optimal solution cannot be guaranteed when using mathematical programming. Therefore, we explore both mathematical programming and meta-heuristic automated options.

We explore this automated approach in close contact with the VF-KDO project and the researchers of the University of Skövde. These researchers include the authors of many articles cited in the literature review: Nourmohammadi, Fathi and Ng. Nourmohammadi was specifically teamed up with us to employ his knowledge of ALBPs to achieve the best results possible in integrating the ergonomics aspect. In this collaboration, we build upon the work earlier done by Nourmohammadi, Ng and Fathi with the Scania pedal car test case: a type II MMALBP including zoning constraints. We then expand this model to include the ergonomics assessment. Thus, our role in the cooperation for the exact method is the incorporation of the ergonomic objective, making this an Ergo-MMALBP including zoning. Moreover, we developed a metaheuristic based on one that was created by University of Skövde for solving SALBPs. In this cooperation, our role consists of using the basis of the developed metaheuristic and writing a new version, adapted to our specific case. For both the exact and metaheuristic method, Nourmohammadi assisted by consulting on choices to be made and sharing the knowledge on the subject. However, we made the eventual decisions, rewrote the code where the basis of University of Skövde did not fit our case and ran the programs.

4.3.1 Exact method: Mixed Integer Program

To solve the pedal car test case problem, we first build a model to try to solve the case in an exact manner. This model is based on previous work of Nourmohammadi, Fathi, & Ng (2020), from the Automation & Production Engineering Department of the University of Skövde. Their model describes a single objective mixed-model assembly line balancing problem that includes zoning constraints. The researchers applied this Mixed Integer Program (MIP) to the Scania Pedal Car test case in the project VF-KDO. In our case, this model needs to be adapted to include the ergonomics aspect and take into account two objectives instead of one. First, we describe the existing basis of the model, after which we expand it to fit our needs.

Original model

The basis of the model is single objective and focusses on minimizing the CT. The model includes the index *i* and *h* for tasks, *j* for stations and *m* for models (in our case the different types of pedal car, red and black). The precedence relations are represented in the parameters $p_{\mathrm{h}i}$, s_{hi} and $psall_{\mathrm{h}i}$, showing whether task *h* is among the immediate predecessors, immediate successors or in the joint parameter of both predecessors or successors, respectively. The zoning constraints are represented in two ways: positive ($zcp_{\mathrm{h}i}$) and negative ($zcn_{\mathrm{h}i}$). Finally, the task times per task per model are required (t_{im}). The decision variables are whether to assign task i to station j (X_{ij}) and whether a task is performed before another task ($U_{\mathrm{h}i}$). These decision variables influence the dependent decision variables CT and C_{im}: the overall CT and the completion time of task *i* for model *m*. The original model contains constraints for task assignment, precedence relations, task sequencing, positive and negative zoning and CT determination. Table 4-1 shows an overview of indices, parameters and decision variables.

Table 4-1. Original model indices, parameters and decision variables

Indices:	
$\boldsymbol{i}$	Task index (i=1,…,nt); nt=number of tasks
$\boldsymbol{h}$	Task index (h=1,…,nt); nt=number of tasks
$\boldsymbol{j}$	Station index (j=1,…,ns); ns= number of stations
$\boldsymbol{m}$	Model index (m=1,…,nm); nm=number of models
Parameters:	
$\boldsymbol{p_{hi}} \in (\boldsymbol{0},\boldsymbol{1})$	1 if task h is an immediate predecessor of task i; 0 otherwise
$\boldsymbol{s_{hi}} \in (\boldsymbol{0},\boldsymbol{1})$	1 if task h is an immediate successor of task i; 0 otherwise
$\boldsymbol{psall_{hi}} \in (\boldsymbol{0},\boldsymbol{1})$	1 if task h is an immediate predecessor or successor of task i; 0 otherwise
$\boldsymbol{zcp_{hi}} \in (\boldsymbol{0},\boldsymbol{1})$	Positive zoning constraint between task h and i
$\boldsymbol{zcn_{hi}} \in (\boldsymbol{0},\boldsymbol{1})$	Negative zoning constraint between task h and i
$\boldsymbol{t_{im}} \in \boldsymbol{R}$	Time of task i for model m
Decision variables:	
$\boldsymbol{X_{ij}} \in$ (0,1)	1 if task i is assigned to station j; 0 otherwise
$\boldsymbol{U_{hi}} \in$ (0,1)	1 if task h is performed before task i; 0 otherwise
Dependent decision variables:	
$\boldsymbol{CT} \in$ Real	Cycle time
$\boldsymbol{C_{im}} \in$ Real	Completion time of task i for model m

The original model by Nourmohammadi et al. (2020):

$Min\ \ OF = CT$

s.t.

$$\sum_j X_{ij} = 1;\ \forall i \tag{1}$$

$$\sum_j j \times X_{hj} \leq \sum_j j \times X_{ij};\ \forall(h,i)|p_{hi} = 1 \tag{2}$$

$$C_{hm} - C_{im} + M(1 - X_{ij}) + M(1 - X_{hj}) \geq t_{im};\ \forall(h,i)|p_{hi} = 1, \forall j, \forall m \tag{3}$$

$$C_{hm} - C_{im} + M(1 - X_{hj}) + M(1 - X_{ij}) + M(1 - U_{hi}) \geq t_{hm};\ \forall(h,i)|psall_{hi} = 0, \forall j, \forall m \tag{4}$$

$$C_{im} - C_{hm} + M(1 - X_{hj}) + M(1 - X_{ij}) + M(U_{hi}) \geq t_{im};\ \forall(h,i)|psall_{hi} = 0, \forall j, \forall m \tag{5}$$

$$C_{im} \leq CT;\ \forall\, i, \forall m \tag{6}$$

$$C_{im} \geq t_{im};\ \forall\, i, \forall m \tag{7}$$

$$X_{hj} = X_{ij};\ \forall(h,i)|zcp_{hi} = 1, \forall j \tag{8}$$

$$X_{hj} + X_{ij} = 1;\ \forall(h,i)|zcn_{hi} = 1, \forall j \tag{9}$$

Equation 1 defines each task must be assigned to a station. Equation 2 ensures that precedence relations are respected. The completion time is defined by equation 3 in case of precedence relations, and by 4 and 5 in case there are no precedence relations, ensuring tasks on the same station do not overlap. Equation 6 sets the CT to the highest completion time, and equation 7 ensures the completion time encompasses a task's entire task time. Equations 8 and 9 ensure zoning constraints are adhered to, positive and negative respectively. In our pedal car test case, there are no negative zoning constraints, but we keep this equation in this original model presentation to show the versatility of the model.

Additional model indices, parameters and decision variables

Next, we add the necessary parameters and (dependent) decision variables to include ergonomics. Each task's REBA score yielded from the data gathering step (Section 4.1) is added as a parameter. Other parameters are added for the weighing of the objectives, as described in the next paragraph. The ergonomic risk score per station is the time-weighted average REBA (TWAR) score. This means that the longer a task takes, the heavier its REBA score is weighed into the stations' TWAR. The ergonomic risk score of a station is first calculated for each model separately (E_{jm}), since the models' tasks and/or task times differ. The station's ergonomic risk score (SE_j) is set to the maximum of all models' ergonomic risk scores of that station. A final score, the maximum ergonomic risk score of all stations (SE_{max}), is also defined. Table 4-2 summarizes the model's additional notations and their descriptions.

Table 4-2. Addition to original model notations and their descriptions

Parameters:	
$\boldsymbol{Reba_i} \in \boldsymbol{R}$	Reba score of task i
$\boldsymbol{\alpha, \beta, \gamma}$	Weights of objectives
Dependent decision variables:	
$\boldsymbol{E_{jm}}$ ∈ Real	Average Reba score of model m in station j
$\boldsymbol{SE_j}$ ∈ Real	Maximum Reba score for station j
$\boldsymbol{SE_{max}}$ ∈ Real	Maximum Reba score of all stations
$\boldsymbol{Z_{ijm}}$ ∈ Real	Intermediate variable for linear notation

Objectives

The new objectives for the MIP are the sum of all stations' ergonomic risk scores and the maximum. These objectives are chosen to represent the ergonomic risks in the assembly line, both in terms of peak reduction and in terms of sum reduction. We combine the objectives the following way:

$$Min\ \ OF = \alpha[CT] + \beta\left[\sum_j SE_j\right] + \gamma[SE_{max}] \tag{10}$$

This objective function (OF) contains the weights α, β and γ to indicate the importance that is being given to the sub objective. To facilitate intuitive weighing of these sub objectives, we choose to normalize the values of the different objectives to all be between 0 and 1. We need the objective values to be in the same range, otherwise the weights assigned to α, β and γ do not intuitively represent the focus of the MIP. We further elaborate on these weights in Section 5.1. The normalization of each of the sub objectives yield the following objective function:

$$Min\ \ OF = \alpha\frac{CT - CT_{min}}{CT_{max} - CT_{min}} + \beta\frac{\sum_j SE_j - (\sum_j SE_j)_{min}}{(\sum_j SE_j)_{max} - (\sum_j SE_j)_{min}} + \gamma\frac{SE_{max} - (SE_{max})_{min}}{(SE_{max})_{max} - (SE_{max})_{min}} \tag{11}$$

The REBA score per task is always between 1 and 15, indicating the TWAR of a station also adheres to these upper and lower bounds. The TWAR does not exceed 15 even when a station only has tasks of REBA score 15. Similarly, the TWAR of a station is never lower than 1, when all tasks in the station have REBA value 1. Thus, the values for $(\sum_j SE_j)_{min}$, $(\sum_j SE_j)_{max}$, $(SE_{max})_{min}$ and $(SE_{max})_{max}$ can be determined by using the formulas 12, 13, 14 and 15, below.

$$(\sum_j SE_j)_{min} = REBA_{min} \times NS = 1 \times NS = NS \quad (12)$$

$$(\sum_j SE_j)_{max} = REBA_{max} \times NS = 15 \times NS \quad (13)$$

$$(SE_{max})_{min} = REBA_{min} = 1 \quad (14)$$

$$(SE_{max})_{max} = REBA_{max} = 15 \quad (15)$$

$$CT_{min} = \frac{\max(\sum_i t_{i1}, \sum_i t_{i2}, \ldots, \sum_i t_{i\,nm})}{NS} \quad (16)$$

For the CT, the theoretical minimum value can be determined based on the case at hand, as shown in equation 16. To find an acceptable CT_{max}, we choose to run the model first for each of the objectives individually. The highest value of CT to appear in these runs, can be used to base a suitable value of CT_{max} on.

Constraints

To the existing constraints in the original model, we add the definition of the ergonomic risk scores. Equation 17 represents the calculation of the TWAR value, for each station and model:

$$E_{jm} = \frac{\sum_{i=1}^{nt} X_{ij} \times t_{im} \times Reba_i}{\sum_{i=1}^{nt} X_{ij} \times t_{im}} ; \forall j, m \quad (17)$$

However, since this equation is multiplying and dividing decision variables amongst one another, this is nonlinear. While non-linear models are sometimes solvable, in general, the complexity of such models is much higher and thus, takes much longer to solve (Rader, Jr., 2010). To avoid the nonlinearity, we rewrite the formula for E_{jm} , see equation 18, below.

$$\sum_{i=1}^{nt} Z_{ijm} \times t_{im} = \sum_{i=1}^{nt} X_{ij} \times t_{im} \times Reba_i ; \forall j, m \quad (18)$$

In this formula, the dependent decision variable Z_{ijm} is introduced to avoid non-linear formulations. To parallel the TWAR calculation, we must define Z_{ijm} to be equal to $E_{jm} \times X_{ij}$. For this, we need the following equations 19, 20, 21 and 22.

$$Z_{ijm} \leq M \times X_{ij} \quad (19)$$

$$Z_{ijm} \leq E_{jm} \quad (20)$$

$$Z_{ijm} \geq E_{jm} - M(1 - X_{ij}) \quad (21)$$

$$Z_{ijm} \geq 0 \quad (22)$$

In this case, M represents a large number, larger than or equal to the upper bound of E_{jm}. This upper bound is 15, same as the upper bound of the task REBA score, since it is the TWAR of all tasks' REBA scores in station *j* for model *m*. The M is also used as a big number in the original model, in equations 3, 4 and 5. We elaborate on the exact value of M in Section 5.3.1. After having calculated E_{jm}, the values of SE_j and SE_{max} can be constrained as shown in equations 23 and 24 below.

$$SE_j \geq E_{jm}; \forall j, m \tag{23}$$
$$SE_{max} \geq SE_j; \forall j \tag{24}$$

The full model after adaptation can be found in Appendix B. We now continue to describe the metaheuristic method of solving the MMALBP.

4.3.2 Meta-heuristic: Genetic Algorithm

In this research, we explore Scania's case by means of the PCTC. However, the reality of Scania's truck assembly line contains much more tasks and variations than the PCTC. Since the MMALBP has been proven to be NP-hard, we expand this research to also include the use of meta-heuristics. Table 5 (in Chapter 3) shows that meta-heuristics have been used by several researchers. Five out of six meta-heuristic papers mention using Genetic Algorithms (GA) (Carnahan et al., 2001; Cheshmehgaz et al., 2012; Barathwaj et al., 2015; Al-Zuheri et al., 2016; Mura & Dini, 2019). Since this is, according to literature, an efficient method of solving NP-hard ALBPs, we also choose to develop a GA to solve our case.

A genetic algorithm is a type of metaheuristic that uses a set of solutions (chromosomes) to generate new ones, by ways of selection, mutation, and crossover. Such approaches were first described by Holland (1975) and mimic the biological process of evolution. This allows new generations to be formed out of old ones, searching through different areas of the solution space. The GA avoids local optima and is able to find good solutions in large combinatorial optimization problems (Al-Zuheri et al., 2016).

We base our GA on the recent developments of Fathi et al. (2020) in the area of ALBP genetic algorithms. While their work focusses on a SALBP type I (minimising number of workstations), it does consider a second objective, making it suitable for our Ergo-MMALBP. Another important feature of their GA is the specific priority based encoding and decoding procedures, which prevent the generation of infeasible solutions. Finally, Fathi et al. (2020) describe the pseudo-code used very elaborately and is thus a good basis to build an Ergo-MMALBP-II adapted GA on.

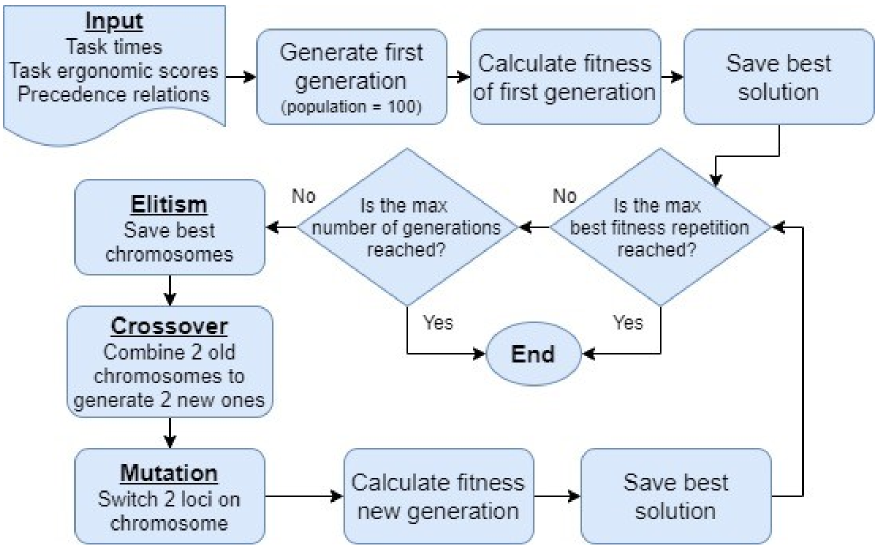

Figure 4-15. Overview of GA mechanics

Figure 4-15 shows an overview of the GA's process, with the stopping criteria best solution repetition and number of generations. We now elaborate on the priority-based encoding, decoding and fitness function evaluation. Next, we describe the operators used to define next generations: elitism, crossover and mutation.

Priority-based encoding

```
Pseudo code: encoding procedure
Input: generation of chromosomes with priorities (pr), number of tasks (N)
Create empty Task Sequences generation (TS)
For each chromosome
    row_pr = pr(Chromosome, :) --> Create copy of priority vector to avoid altering original
    for each locus on chromosome
        for prio = 1 to N
            find which task has priority prio
            Check if that task's predecessors have been scheduled
            if so
                TS(chromosome, locus) = task --> Schedule task
                row_pr(task) = 0 --> skipped from now on
                break --> Stop looking for next highest priority & go to next locus
            end
        try next highest priority
    Next locus
Next chromosome
```

Pseudo code 1. Encoding procedure

We base our own GA on the GA described by Fathi et al. (2020) and fully incorporate their method for priority based encoding. Their encoding procedure uses the input of priority vector: a vector of size N (where N = number of tasks) with priority values ranking also from 1 to N. Each priority value occurs only once and for the initial generation, these values are randomly assigned. Future generations' priority vectors are generated by the elitism, mutation and crossover operators. The index of the priority value in a vector is the task number. Table 4-3 illustrates the priority vector of one chromosome. Fathi et al. (2020) then describe the encoding process as follows: the process starts by trying to assign a value to locus 1, and explores which task that can be scheduled according to precedence, has the lowest priority. It assigns this task to the locus and continues for the next locus until all loci are assigned a task value. This process thus generated the vector with task numbers in a certain sequence, that is called the Task Sequence (TS). This encoding procedure is described more specifically in Pseudo code 1. Based on the procedure and the example of 10 tasks, shown in Table 4-3 and Figure 4-16, we illustrate how the encoding procedure works.

Table 4-3. Example of priority vectors

Tasks	1	2	3	4	5	6	7	8	9	10
Chromosome 1	5	2	6	10	3	1	9	4	7	8

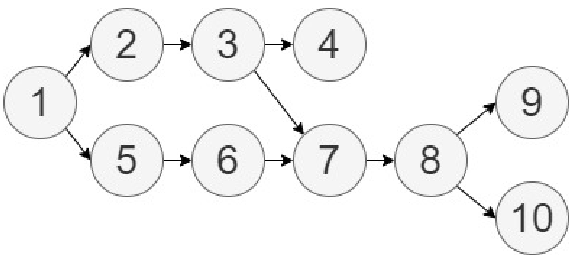

Figure 4-16. Example precedence

The encoding procedure starts with an empty TS. In the priority vector, we find priority number 1 is allocated to task number 6. The encoding procedure then checks whether it is possible to schedule task 6 to the TS. Since none of the predecessors (tasks 1 and 5) are scheduled yet, it cannot schedule task 6. It then checks the next priority, which is assigned to task 2. Again, this task cannot be scheduled yet. The encoding procedure continues with this until we arrive at priority 5, which is assigned to task 1. This task can be scheduled, since it has no predecessors, so TS is now [1]. When a task has been scheduled, it is no longer considered in our search. We then continue to find the task to put on the second locus, restarting from priority 1. Again, task 6 cannot be scheduled, it requires task 5 to be scheduled. Priority 2 is assigned to task 2, which can be scheduled, making our TS [1,2]. For the third locus, task 6 is again considered but still infeasible in terms of precedence, followed by task 5 (priority 3). This task can be assigned, making the TS [1,2,5]. This process is continued until all tasks are assigned, resulting in TS [1, 2, 5, 6, 3, 7, 8, 9, 10, 4]. This way, this encoding procedure results in a TS for each chromosome.

Decoding

```
Pseudo code: decoding procedure
Input: TS
For each chromosome in generation
    Initialize:
    E1 = random integer between 1 and N-2
    E2 = random integer beteen E1+1 and N-1
    Stime = Ø
    Assignment:
    For task = 1 to E1
        Add task to Station 1
    end
    For task = E1+1 to E2
        Add task to Station 2
    end
    For task = E2+1 to N
        Add task to Station 3
    end
    for k = 1 to 3
        Calculate station busy time: Stime(k)
    end
```

Pseudo code 2. Decoding procedure

The decoding procedure is defined by Fathi et al. (2020) as the procedure that assigns tasks from a TS to stations. Since the decoding procedure of Fathi et al. (2020) is focussed on opening a minimal number of stations and employs a fixed CT, we cannot use the same decoding procedure. Thus, we write a decoding procedure that fits with our parameters and aims. This decoding procedure works with randomly generated endpoints for stations (E-values). Since our pedal car test case has 3 stations, we have E1 and E2 as the endpoints of station 1 and 2, respectively. These endpoints are an integer value between 1 and N and indicate the index in the task sequence after which the tasks are assigned to the next station. We use the same example as the encoding procedure, where we yielded the TS [1, 2, 5, 6, 3, 7, 8, 9, 10, 4]. If E1 equals 3 and E2 equals 7, the tasks would be distributed over the stations as follows: Station 1 [1, 2, 5], Station 2 [6, 3, 7, 8], Station 3 [9, 10, 4]. This then yields the station times: the busy time of a station with the assigned tasks. Both the tasks assigned to each station and the stations' busy times are necessary to calculate the fitness function. To avoid storing them in a large vector, the fitness function calculation is executed in the same for-loop as the decoding is done, hence the missing 'end'-statement at the end of Pseudo code 2.

Fitness function evaluation

To align the performance of the GA with the performance of the MIP, the formula that assesses a chromosome's fitness is equal to that of the MIP, as shown below.

$$Min\ \ OF = \alpha \frac{CT - CT_{min}}{CT_{max} - CT_{min}} + \beta \frac{\sum_j SE_j - (\sum_j SE_j)_{min}}{(\sum_j SE_j)_{max} - (\sum_j SE_j)_{min}} + \gamma \frac{SE_{max} - (SE_{max})_{min}}{(SE_{max})_{max} - (SE_{max})_{min}}$$

We employ the same maximum and minimum values for all the objectives as in the MIP and, similarly, we only ever combine two objectives at the same time: CT and one of the two ergonomic objectives $\sum_j SE_j$ or SE_{max}. Pseudo code 3 shows the process of the fitness function evaluation.

```
Pseudo code: fitness function procedure
Input: TS, Stations' tasks for each chromosome, minCT, maxCT, Weights of objectives (w1, w1, w3)
    SolutionCT = max(Stime)
    for each station
        for each model
            total_time= Sum(t(assigned tasks, model))
            total_time_reba = sumproduct (REBA scores of assigned tasks, t(assigned tasks, model))
            Station_Model_reba = total_time_reba / total_time
        end
    end
    StationREBA = vector or max value of Station_Model_reba per model
    REBAmax = max(StationREBA)
    REBAsum = sum(StationREBA)
    FF= w1 × ((SolutionCT-minCT)/(maxCT - minCT)) + w2 × ((REBA_max - 1)/14)
    + w3 × ((REBA_sum - NS)/(45-NS));
end
```

Pseudo code 3. Fitness function evaluation

Next, we describe the elitism, crossover and mutation operators in general to generate a new generation of solutions. Specific parameter values are defined in Section 5.3.2.

Elitism

The elitism operator ensures that the best performing solutions of a generation are preserved without alterations. The reproduction rate (n_r) defines which portion of a population is thus reproduced in the next generation.

Crossover

The crossover operator consists of a two-point based weight mapping crossover operation. This means that between two points of two parent chromosomes, the weights of the priorities are established and are crossed over between the two parents, generation two new priority vectors and thus chromosomes. The crossover is performed based on the crossover rate (n_c) and parents are selected based on the roulette wheel selection method. This method ensures that parents with better fitness functions are more likely to be selected for crossover (Man, Tang, & Kwong, 1999). We explain the crossover process using an example. Two parents are selected to cross over using the roulette wheel method; in this case we take chromosomes 1 and 2, as shown in Figure 4-17. Next, two loci are selected to form the interval in which the crossover will take place.

Selected interval

	Tasks	1	2	3	4	5	6	7	8	9	10
Priority	Chromosome 1	5	2	6	10	3	1	9	4	7	8
	Chromosome 2	3	5	4	6	1	8	2	9	10	7

Figure 4-17. Crossover interval

After selecting the interval, the weights of the priorities in the interval is defined: the lowest priority value gets assigned weight 1, the next lowest 2, etc. Then, the weights of priorities are crossed over between the two loci. This then ensures the priority values of the loci are not in the same location anymore. For explanation purposes, Figure 4-18 shows this process with the priority values in the interval left blank.

Parents

Tasks	1	2	3	4	5	6	7	8	9	10
Chromosome 1	5	2	6	10	3	1	9	4	7	8
Weight of priority	-	-	3	5	2	1	4	-	-	-

Weight of priority	-	-	3	4	1	5	2	-	-	-
Chromosome 2	3	5	4	6	1	8	2	9	10	7

Crossover

Offspring

Tasks	1	2	3	4	5	6	7	8	9	10
Chromosome 1	5	2						4	7	8
Weight of priority	-	-	3	4	1	5	2	-	-	-

Weight of priority	-	-	3	5	2	1	4	-	-	-
Chromosome 2	3	5						9	10	7

Figure 4-18. Crossover operation

The new (offspring) chromosomes 1 and 2 are then rebuilt by finding which priority value in the interval was lowest and assigning it to the new weight of priority 1. The next lowest priority value in the interval is assigned to the next weight of priority, etc. This continues until all priority values have found their new loci, and the offspring chromosomes are complete, as can be found in Figure 4-19. Crossover result.

Offspring

Tasks	1	2	3	4	5	6	7	8	9	10
Chromosome 1	5	2	6	9	1	10	3	4	7	8
Weight of priority	-	-	3	4	1	5	2	-	-	-

Weight of priority	-	-	3	5	2	1	4	-	-	-
Chromosome 2	3	5	4	6	2	1	8	9	10	7

Figure 4-19. Crossover result

Mutation

The mutation rate (n_m) defines how often chromosomes generate offspring using this procedure. The mutation operator selects a chromosome and exchanges two of its loci. This process is illustrated by Figure 4-20.

Mutation loci

Tasks	1	2	3	4	5	6	7	8	9	10
Parent chromosome	5	2	6	9	1	10	3	4	7	8

Mutation

Offspring chromosome	5	10	6	9	1	2	3	4	7	8

Figure 4-20. Mutation operator

Finally, the new generation is complete and the fitness of all chromosomes is examined. Based on the best fitness score of the new generation, two possible scenarios occur. In case of a new best solution in the most recent generation, the previously best solution is replaced, bringing the best solution repetition counter back to zero. In case there is no fitter solution in the new generation, the best solution repetition counter is incremented and the algorithm checks whether the stopping criteria are met. In the next chapter, we describe the results acquired by application of the GA and other approaches described in this chapter.

4.4 Summary

In this chapter, we explore the approaches necessary to reach our goal of including ergonomics as an objective in the assembly line balancing process. The data gathering required is split into ergonomic data gathering and precedence relations and zoning constraints. The ergonomic data gathering is done by connecting the software tool IMMA with the currently used balancing software AviX. We supported this connection by serving as a test user. The connection is used to easily transfer simulated ergonomic assessment data acquired in IMMA to AviX. The precedence relations and zoning constraints for the pedal car test case are gathered by inspecting the assembly process and assessing practical sequencing considerations.

We move on to explore the manual approach of balancing. We design experiments using the new version of AviX which includes the ergonomic data. Experiments A1 and A2 represent the current way of working: creating a balance without any ergonomic data and improving that initial balance based on ergonomic feedback. Experiment B represents the suggested new manual approach, where the ergonomic data is available and accessible for the process engineers from the beginning.

Finally, the automated approaches include a mixed integer program and a genetic algorithm. The mixed integer program is composed by adding ergonomic constraints to previous work. The calculation of the time weighted average REBA score is initially nonlinear and is rewritten to fit a linear model. The genetic algorithm is also composed of previous work, in which priority-based encoding ensures no infeasible solutions are explored. The decoding procedure is rewritten to fit our objectives: minimizing CT and ergonomic objectives. Finally, elitism, crossover and mutation operations compose the evolutionary aspect of the genetic algorithm and ensure the evolution of the generations of solutions. The performance of the manual and automated approaches on the pedal car test case are explored in the next chapter.

5 Pedal car test case performance

The pedal car test case is used to assess the feasibility and functionality of the approaches described in the previous chapter. This chapter thus contains the answer to the question "What is the performance of the current process and alternative approaches when applied on the pedal car test case?". First, we assess the applicability of the pedal car test case to Scania's truck assembly balancing process and the performance measures that fit both (Section 5.1). Furthermore, in Section 5.2 we assess the performance of the different approaches using pedal car test case.

5.1 Pedal car test case applicability

The pedal car test case is a simplified representation of manual assembly work. This use case is generic enough to not divulge company information but can include complexities such as mixed-model characteristics in this case. However, there are many differences with real truck assembly line processes. We list some of the most important differences in assembly line balancing:

- **Number of operators**. The PCTC assumes there are 3 stations, with one single operator per station. Thus, there is the simplicity of one position standard (PS) per station, indicating one set of tasks for one person. In the truck assembly line, there are mostly more PSs per station, over which the tasks assigned to a station have to be distributed.
- **Location of operators**. Continuing the previous point, on the truck assembly line the tasks are assigned a location label to indicate where on the truck the task takes place (front/middle/rear, left/right). These locations are taken into account when assigning the tasks of a station to a PS, so the operator does not have to walk around the truck and/or other operators as much.
- **Variant workers**. Besides the normal PSs of a workstation, in reality, variant workers can be assigned to a station if a variant will cause the takt time to be exceeded.
- **Variant mix.** In the PCTC we assume the variants can be assembled on the same assembly line, but do not attach a frequency of occurrence to the variants. In reality, the process engineers look at the frequency-weighted mix of the variants in balancing and try to optimize the use of the takt time based on that.
- **Number of tasks and precedence relations.** As mentioned before, the PCTC is a tiny case compared to the number of tasks and precedence relations involved in assembling an entire truck.

Currently, we use the PCTC to explore a novel way of balancing by including ergonomics. We are testing the suitability of a now immature methodology. For such an application the PCTC in its current form is very useful and applicable. Further exploration of the applicability of the current research and scalability to real truck assembly is explored in Chapter 6. We now discuss the performance measures that need to be included to yield applicable results.

Performance measures

The performance measures used in the manual approach and automated approaches have already been introduced in Chapter 4. These are the CT, and the ergonomic measures SUM and MAX. We now discuss in what way to combine these KPIs and why. The current balancing process is aimed at maximum productivity. In the current balancing process that is translated to trying to use the takt time available optimally (between 90 and 100%). However, since we do not have a takt time for the PCTC, we will employ the KPI of CT to reach similar results: using as little time as possible to do all the tasks necessary.

The ergonomic objectives of SUM and MAX have different aims: to reduce ergonomic risk over the totality of the assembly line and reducing the peak ergonomic risks in the assembly line, respectively.

Both these ergonomic objectives are applicable to the PCTC as well as the truck assembly line. We argue that we will not use these objectives simultaneously, since they both represent a different type of ergonomics optimization. Moreover, we are interested to find which results focusing the ergonomics on one at a time will yield. The combination of CT with either of the ergonomic objectives is expected to be conflicting: we expect an optimal assembly line in terms of CT to have bad ergonomics and vice versa.

We then come to the distribution of objective weights for the manual and automated approaches. We chose to explore the results of a 50-50 distribution of weights on CT and one of the ergonomic objectives. Since the manual approach is executed by human beings, we find it is unreasonable to expect them to distribute their focus on the separate objectives by very specific percentages. A distribution of 50-50 is reasonable to expect from the participants, while this can never be measurable. We also argue that the current immaturity of the methodology makes using a 50-50 distribution a reasonable starting point.

5.2 Performance of manual approach

For the manual approach of the balancing process, we ask participants to conduct experiments as described in Section 4.2. We first elaborate on these participants and their relevant knowledge and experience in Section 5.2.1, after which we elaborate on the results yielded by these manual experiments in Section 5.2.2.

5.2.1 Participants

The participants (n=13) were approached by us and by the developers of AviX. The request for participants, including a description of requirements for suitable participants, can be found in Appendix C. We have included participants from multiple Scania production units' process engineers and other balancing-related employees within Scania. We also included participants from another large automotive manufacturing company using AviX in their balancing and from a manufacturing development and service provider. The participants come from different countries in Europe, Asia and South America. The aggregated responses to the before questionnaire can be found in Appendix C. We summarise the education of the participants on the topics of assembly line workload balancing and ergonomics in Figure 5-1. The 'other' responses in both categories consist mostly of work experience.

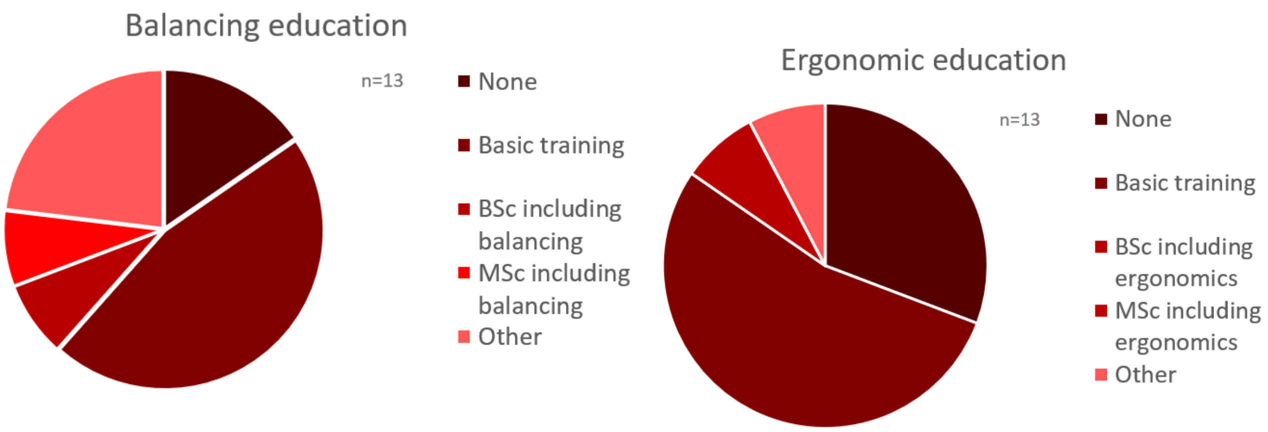

Figure 5-1. Participants' education in balancing (left) and ergonomics (right)

Figure 5-2. Participants' self-rated knowledge

We also asked the participants to rate their own knowledge of line balancing, AviX and ergonomics from 1 to 5 stars. This yielded the average stars as shown in Figure 5-2. The number of years of experience in these same three fields is shown in Figure 5-3. As described in Section 4.2, we requested process engineers to participate if they had experience with balancing and the AviX software for balancing. Therefore, we expected most of the participants to have more than 2 years of experience in those categories, as is the case. For ergonomics, however, we note that 10 out of 13 participants have little or no experience with this aspect. While this is not required for participation, we do draw the conclusion that this might be an improvement recommendation for future process engineers if ergonomics is an incorporated aspect in the line balancing process.

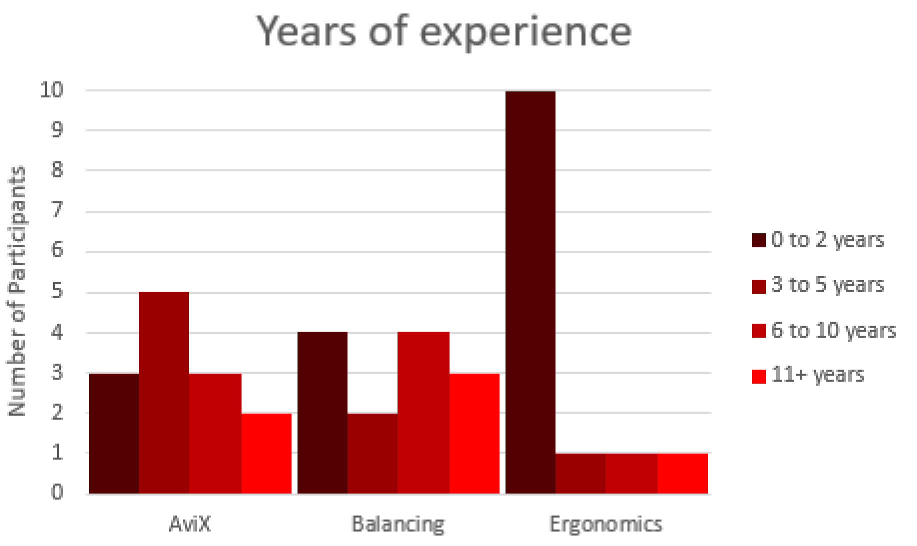

Figure 5-3.Participants' years of experience

Finally, from participants' descriptions of their experiences, we deduce the following. The experiences of participants with AviX software consists of using, teaching or developing the software. Most participants are involved in operational line balancing, but some also give training to others or help develop balancing methods. Finally, all participants have a basic understanding of what the aspect of ergonomics entails. Half of the participants mentions being familiar with specific ergonomic standards, such as SES is for Scania, and some applied these in practice.

5.2.2 Experiment results

The experiments consist of three parts: A1, A2 and B, as described in Section 4.2. The best results for each part and each KPI are shown in Table 5-1 (note: these results are not necessarily obtained by the same participant). First, we elaborate on the results of the three parts separately, after which we evaluate the performance effects of the differences in ergonomic knowledge.

Table 5-1 Overview of best scores

Objective	MIN CT	MIN SUM	MIN MAX
A1	112.5	8.909	3.181
A2	113.2	8.978	3.157
B	113.8	8.603	3.020

Results A1

In Experiment A1, the participants were asked to create the best balance as they would normally in AviX. Since the participants only have information about task times, their only data-driven objective was CT. Figure 5-4 shows a histogram of the CT scores yielded by the participants. These are most frequently between 112 and 114 seconds, and some outliers exceed 120 seconds of CT. In exercise A1, the lowest CT that was achieved was 112.5 seconds. For the ergonomic scores, the lowest SUM value that was achieved was 8.828, while the minimum MAX value that was achieved was 3.181. An overview of all best values is shown in Table 5-1. Since the objectives CT and ergonomics are conflicting, these best values were not yielded by one participant. Even within the ergonomic scores, the best SUM and MAX were yielded by two different participants. We believe this is due to the different aims of these two ergonomic objectives: one is to reduce peak ergonomic risks and one to reduce total ergonomic risk. Figure 5-5 and Figure 5-6 show the pareto frontier of the participants' performance in terms of CT & SUM and CT & MAX, larger images can be found in Appendix D.

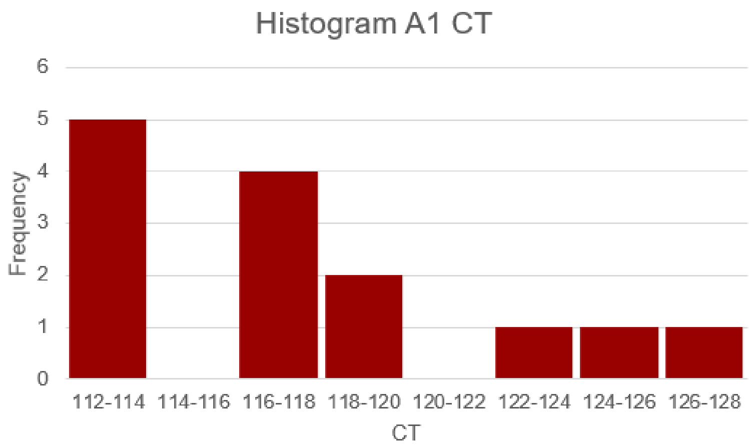

Figure 5-4. Histogram of participants' A1 CT scores

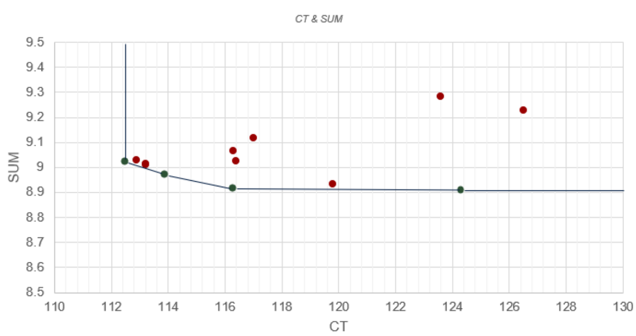

Figure 5-5. A1 Pareto Frontier CT & SUM

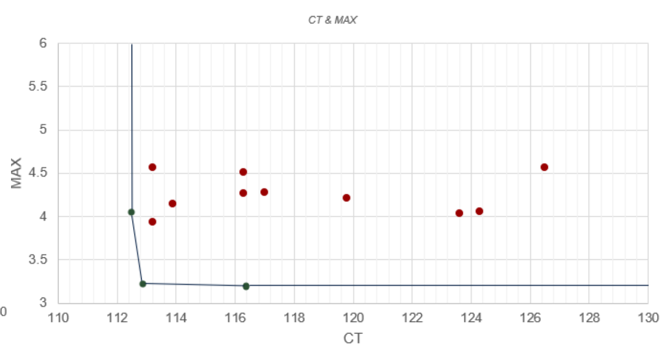

Figure 5-6. A1 Pareto Frontier CT & MAX

After A1, the participants received feedback on their ergonomic scores. The feedback for each participant consisted phrasing similar to the following: "*Currently, your station [X] has the worst ergonomics score of the three. Try to rearrange some tasks to improve this*", where [X] is the participants' worst station number. We chose to use this shape of feedback to imitate the current Scania situation, where an ergonomist assesses the stations and position standards and can direct the process engineers to rebalance the worst ones. The exact station ergonomic scores and the feedback given is shown in Appendix D. Furthermore, the full results of all participants are also shown in Appendix D.

Results A2

After receiving the feedback, the lowest CT that was achieved was 113.2 seconds. The best ergonomics scores were 8.978 and 3.157 for SUM and MAX, respectively (see Table 5-1). The increase in best CT value compared to A1 was to be expected, since the participants' aim was to improve the ergonomics in this deliverable and ergonomics and CT are conflicting objectives. However, it is interesting to note that the best SUM value of A2 is higher than the best SUM value of A2. We did expect the best MAX value to decrease, since we point out the station with the worst ergonomics in the feedback, thus inciting peak reduction. Figure 5-7 and Figure 5-8 show the pareto frontiers of this experiment (for larger images, see Appendix D).

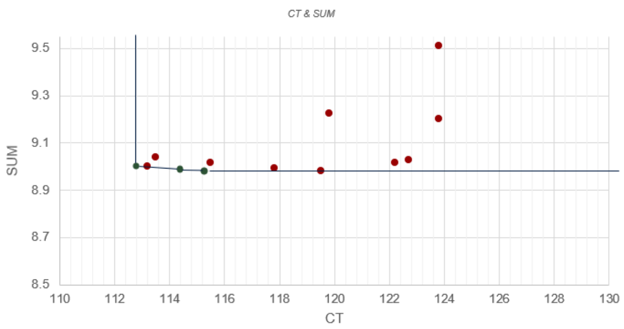

Figure 5-7. A2 Pareto Frontier CT & SUM

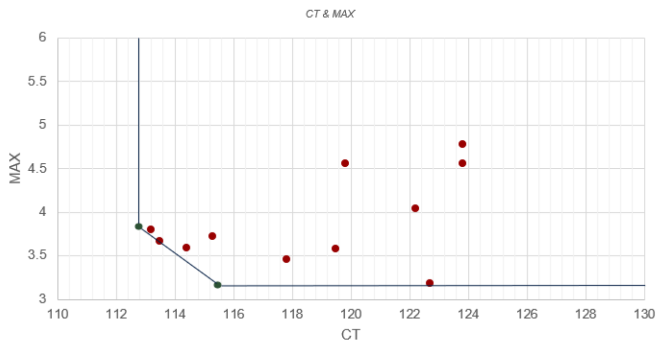

Figure 5-8. A2 Pareto Frontier CT & MAX

We compare these results to the results of A1 and note less vertical spread in the CT & SUM graphs, but the maximum SUM value has worsened in A2. in the CT & MAX graphs, we see more participants with better MAX values, but this is not the case for all participants. Judging from these observations, we cannot easily draw a conclusion. Statistical analysis might show whether the results are ergonomically better (as expected) or worse, and whether the CT is affected negatively (as expected). To evaluate whether there is a significance difference in the participants' results on both experiments, we perform the Wilcoxon matched pairs signed ranks test. This test is appropriate because we have the same sample of people performing two experiments, creating matched pairs of data. Also, we have a small sample size (n=13) and cannot assume normality in the results (Sheskin, 2000).

We analyze each objective separately and construct our hypotheses one-tailed. The null hypothesis (H_0) is that there is no difference between A1 and A2. The alternative hypotheses are constructed by assuming the CT will increase when ergonomics is included and assuming both SUM and MAX ergonomic values will decrease when ergonomics is included. We use a confidence limit of 95% and reject H_0 if the p-value is lower than 0.05. The analysis was done using the statistical software program SPSS, and the output is shown in Appendix E for all statistical analyses. Using this one-tailed test for each of the objectives, we can draw the following conclusions:

- CT values **are not** significantly increased when including ergonomic feedback (p=0.285).

- Ergonomic SUM scores **are not** significantly decreased when including ergonomic feedback (p=0.507).
- Ergonomic MAX scores **are not** significantly decreased when including ergonomic feedback (p=0.055).

We can now state that during these experiments, the effect of ergonomic feedback on an existing balance does not have the desired effect on the ergonomic scores, nor does it have the expected effect on CT values.

Results B

After the initial experiment representing the current way of working, we now continue with the new balancing process. In this process, the process engineer has access to ergonomic data to include in his balancing decisions. In experiment B, the participants were asked to create the best balance in terms of CT and ergonomics. Figure 5-9 and Figure 5-10 show the (zoomed in) pareto frontiers of the participants' performances. For larger images and the full pareto frontier graphs, see Appendix D.

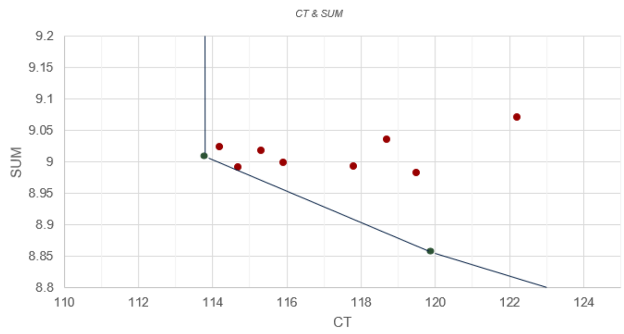

Figure 5-9. B Pareto Frontier CT & SUM (zoomed in)

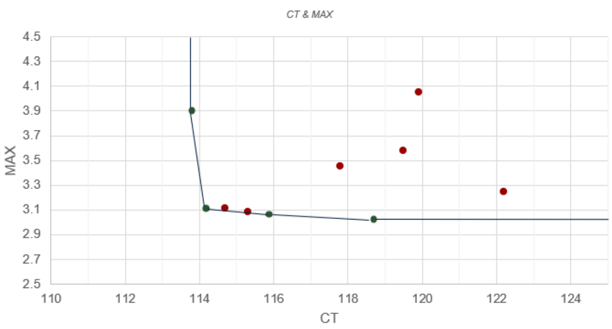

Figure 5-10. B Pareto Frontier CT & MAX (zoomed in)

In this case, we observe the participants' results are closer together, which is the reason for the zoomed in view on the pareto frontier graphs. This closeness can indicate the participants are more guided in their balancing process. However, we still cannot draw obvious conclusions as to whether the results are truly ergonomically better than in experiment A1 and A2. Thus, we again perform statistical analysis using the Wilcoxon matched pairs signed ranks test. The null and alternative hypotheses are the same as in the comparison of A1 with A2. First, we compare the results of A2 with experiment B, enabling us to draw the following conclusions

- CT values **are** significantly increased when providing participants with ergonomic data instead of only ergonomic feedback (p=0.031).
- Ergonomic SUM scores **are not** significantly decreased when providing participants with ergonomic data instead of only ergonomic feedback (p=0.099).
- Ergonomic MAX scores **are** significantly decreased when providing participants with ergonomic data instead of only ergonomic feedback (p=0.003).

Similarly, we compare the results of A1 with the result of B, to examine the effect of balancing with ergonomic data from the beginning of the process. We can draw the following conclusions:

- CT values **are** significantly increased when providing participants with ergonomic data from the beginning (p=0.047).
- Ergonomic SUM scores **are** significantly decreased when providing participants with ergonomic data from the beginning (p=0.013).
- Ergonomic MAX scores **are** significantly decreased when providing participants with ergonomic data from the beginning (p=0.000).

We can now draw the conclusion that when the ergonomic data is accessible and visible for process engineers from the beginning of balancing, their balance with the combined objective of best CT and best ergonomics, yields a higher CT than without ergonomic data but also yields lower ergonomic risks.

5.2.3 Participants' feedback and suggestions

We now summarize the results of the questionnaire that participants have filled in after doing the experiments, the full aggregated results can be found in Appendix C. In this after-questionnaire we asked the participants about the clarity of the explanation, the dataset and the assignment, and the level of support they received from us researchers. From the options 'good', 'mediocre' and 'bad', most participants rated all these aspects 'good'. No 'bad' ratings were given to any aspect. The clarity of dataset was rated worst, with nine 'good' ratings and four 'mediocre'. We hope to have made up the unclear dataset for those concerned by our level of support, which was rated 'good' by twelve out of thirteen participants.

We also requested feedback on the time required for participating, to be judged as 'too short', 'just right' and 'too long'. For both the introduction meeting and the A2 assignment, all participants felt the time spent was 'just right'. The time spent on A1 was rated 'just right' twelve times and the time spend on assignment B was rated 'just right' 11 times. From these time ratings and the ratings given to the clarity and support, we conclude the participation of our experiments was successful overall and that participants' expectations were managed adequately.

The remaining questions about the experiments concern the opinions of participants on experiments A1 & A2, experiment B, comparing A with B and the method of including ergonomics. We distil the most frequently occurring answer statements (in similar wording). Experiment A (assignments A1 & A2) was said to be a representation of normal balancing. Experiment B was met with many positive comments and was deemed interesting and useful. In comparing experiment A to B, the most frequent conclusion was that it was a good improvement. About including ergonomics in the balancing process in this way (as done in experiment B), many were also positive.

Provided suggestions on including ergonomics in balancing are very broad and some mention limitations as also already mentioned in Section 5.1, concerning the simplicity of the experiments' PCTC. Other suggestions were:

- to include an aim or a threshold for the aggregated ergonomic risk score, which must be met in order to have a balance be approved.
- to define the costs of ergonomics, so that a weighing can be made how much CT can be sacrificed for the benefit of better ergonomics.
- to calculate the aggregated ergonomics score based on a work shift, instead of a single takt. Likewise, including task rotation in the calculations is mentioned.
- to explore the influence of workplace design on ergonomic scores.

We include several of these suggestions in our recommendations, in Chapter 7. All the suggestions can be found in Appendix C. In the following section of this chapter, we move on from manual balancing to automated balancing approaches, and assess their performance compared to the results presented so far.

5.3 Performance of automated approaches

The automated approaches consist of the MIP and the GA, as described in Sections 4.3.1 and 4.3.2, respectively. We conducted experiments with the same dataset as provided to the (manual) participants, and we describe performance of the MIP in Section 5.3.1 and of the GA in Section 5.3.2.

5.3.1 Exact method: MIP

As mentioned in 4.3.1, the objective function of the MIP combines three objectives: CT, SUM and MAX. For running this MIP model, we use the General Algebraic Modelling System (GAMS) software (version 24.1.2 as done by the researchers with their earlier MIP model (Nourmohammadi, Fathi, & Ng, 2020). This software uses a CPLEX optimization software package as its solver and was run on a computer with a Core i9 processor and 64GB RAM. Since the MMALBP problem at hand is NP-hard, we do not expect the MIP model to reach an optimal solution, and thus a gap of 0. Therefore, we use a time cap to restrict the model from looking any further after 20,000 seconds. For the large value parameter M, we take the value 200. This value was used by the original model for its constraints and also adheres to the newly added constraints' bounds.

To be able to fill in the parameters necessary in the objective function (Equation 11, shown again below), we need to establish the maximum value of CT. To do this, we first run the model for each of the objectives separately, to determine this upper bound. In Table 5-2, these runs are shown as scenarios 1, 2 and 3. The objectives used for these scenarios can be found in Appendix F.

$$Min\ \ OF = \alpha \frac{CT - CT_{min}}{CT_{max} - CT_{min}} + \beta \frac{\sum_j SE_j - (\sum_j SE_j)_{min}}{(\sum_j SE_j)_{max} - (\sum_j SE_j)_{min}} + \gamma \frac{SE_{max} - (SE_{max})_{min}}{(SE_{max})_{max} - (SE_{max})_{min}} \tag{11}$$

Table 5-2. MIP results

Scenario	CT	SE$_j$			SUM	MAX	CPU	GAP
		S1	S2	S3				
1 (CT)[a]	112.00	2.733	3.895	2.390	9.018	3.89464	20000	0.009[b]
2 (SUM)[a]	205.38	1.000	3.359	2.435	6.794	3.35900	20000	0.283
3 (MAX)[a]	182.60	1.000	3.001	3.001	7.001	3.00055	821	0.000
4 (CT & SUM)	112.78	3.065	2.199	3.728	8.991	3.72768	20000	0.635
5 (CT & MAX)	112.20	3.089	3.136	2.778	9.003	3.13608	20000	0.139

[a]Scenario run with separate objective functions: see Appendix F.
[b]Manual input CT lower bound of 111, based on theoretically lowest possible CT

After running Scenarios 1, 2 and 3, we can fill in the objective function. For the CT_{max} value we select the highest CT of scenarios 1, 2 and 3, and go a bit above this value to ensure the CT objective is normalized to a value between 0 and 1. Since the highest attained CT is 205.38 seconds in scenario 2, we choose to work with $CT_{max} = 220$. Our PCTC contains 3 stations, $NS = 3$, yielding the following objective function in Equation 25.

$$Min\ \ OF = \alpha \frac{CT - 111}{220 - 111} + \beta \frac{\sum_j SE_j - 3}{45 - 3} + \gamma \frac{SE_{max} - 1}{15 - 1} \tag{25}$$

We then run the scenarios with combined objectives, and we use $\alpha = 0.5$ in both instances. For scenario 4, combining the CT objective with the ergonomic SUM objective, we use $\beta = 0.5$ and $\gamma = 0$. Scenario 5, combining CT and MAX, uses $\beta = 0$ and $\gamma = 0.5$. This yields the results shown in Table 5-2. The task distribution of each of these scenarios can be found in Appendix G.

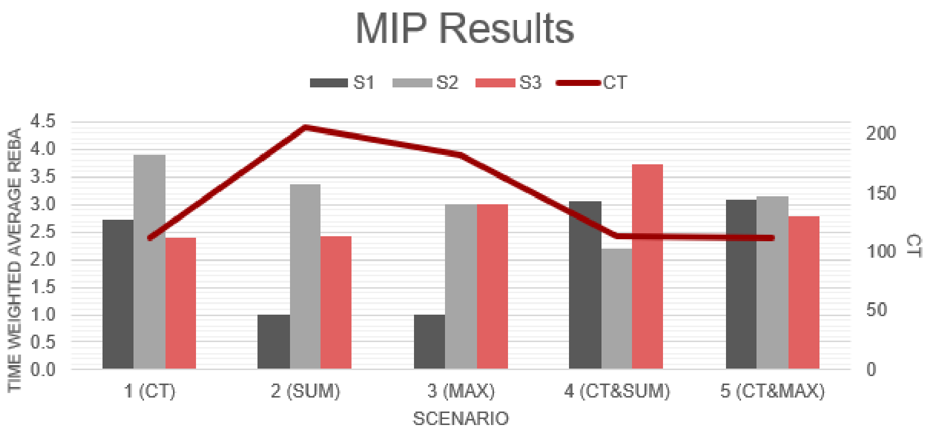

Figure 5-11. MIP Results

Figure 5-11 shows the MIP results graphically, and clearly shows the single objective runs have larger differences in ergonomic scores between stations. We notice scenario 3 (MAX) has equal ergonomic scores for stations 2 and 3, but not for 1. We believe this is caused by an initialisation task that is included in the dataset, necessary to indicate precedence relations. This task does not contain any activity for an operator and has thus been assigned a task time of 0.0001, and a REBA score of 1. Both scenario's 2 and 3 have found their best solutions in assigning only this initialisation task 1 to station 1. We can reason that this occurs because the other tasks with lower REBA scores can then be used to compensate for the tasks with higher REBA scores in the TWAR of the two remaining stations. This creates task distributions that, in practice, are not realistic. However, when we look at the scenarios combining CT and ergonomics, this is no longer a problem. Since we assume to always include CT as an objective in realistic balancing activities, we believe the combination of this dataset with the current model constraints is still valid.

We now compare the results from the MIP's combined objective runs (scenarios 4 and 5) to the manual experiment results. To do so, we provide the (zoomed in) pareto frontier graphs of the manual experiments and introduce the MIP results (labelled 4 and 5) and the new pareto frontier in light blue. Figure 5-12 shows the results from the CT & SUM combination of objectives, corresponding to MIP scenario 4. While MIP scenario 4's result is on the pareto frontier, it is only just so, as MIP scenario 5 (CT & MAX) has a better CT and only slightly worse SUM value.

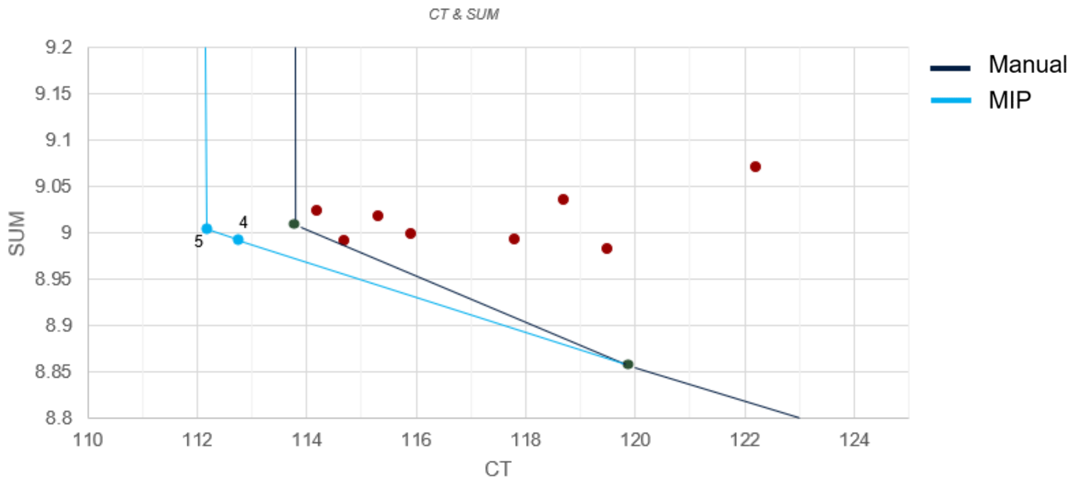

Figure 5-12. Manual experiment B pareto frontier including MIP (CT & SUM)

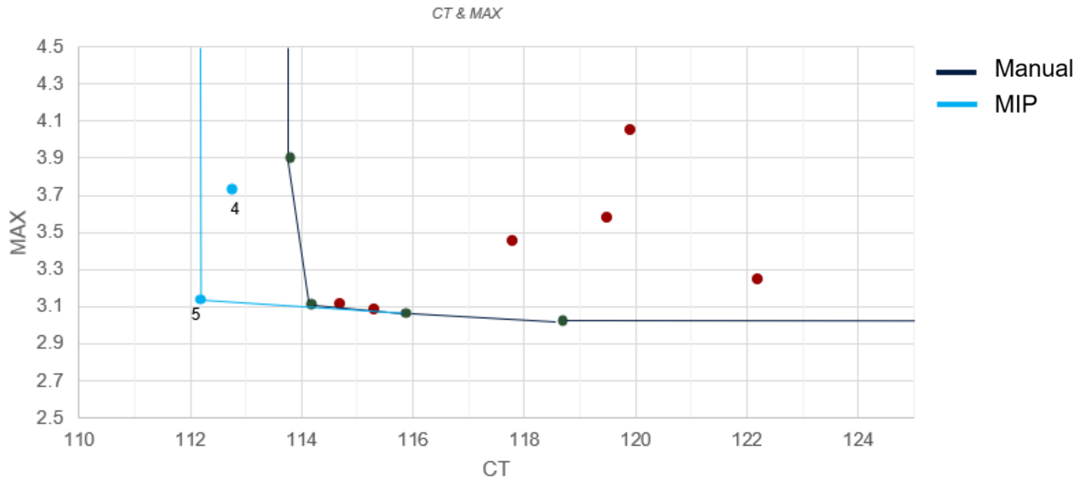

Figure 5-13. Manual experiment B pareto frontier including MIP (CT & MAX)

Figure 5-13 shows the results from the CT & MAX combination of objectives, corresponding to MIP scenario 5. In this case, the MIP scenario 5 result is indeed much better than the MIP scenario 4 result, which is not in the pareto frontier. Interestingly, these two graphs suggest that focussing on CT & MAX ensures that the CT & SUM objectives are not very bad either, making the CT & MAX combination maybe more useful for future automated optimization in practice.

Finally, we can argue that while the MIP results shifted the pareto frontiers, the new frontiers do still include some manual results. This shows that the manual optimization method is not fully outperformed by this automated method and is worth considering for practical application.

5.3.2 Meta-heuristic: GA

The other automated approach is the GA. This GA, described in Section 4.3.2, was built to include ergonomics in the balancing process. However, it is not currently suitable for considering zoning constraints. Similar to the manual approach, we decide to bundle the tasks into their zones and use that as the input data of the GA. The zones dataset can be found in Appendix H and the zones' precedence relations are used as input, same as used in the manual experiments.

The GA contains several parameters that can be changed to benefit the performance of the algorithm. For the weighing of the objectives, we use the same weights as in the MIP runs described in Section 5.3.1. The remaining parameters are the population size (popsize), replication rate (n_r), crossover rate (n_c), mutation rate (n_m) and the stopping criteria total number of generations (G) and best solution repetition (BSR). Our GA is based on the research of Fathi et al. (2020), who assessed many different problems with their GA. Since they had a wider variety of cases, we assume their population size and their replication, crossover and mutation rate have yielded sufficient exploration and exploitation of the solution space. This means the good solutions are exploited further by replication and by using the roulette wheel selection method in the crossover, while local optima are avoided by using the crossover and mutation operators. We thus assume the following parameters: popsize = 100 chromosomes, n_r = 0.2, n_c = 0.8 and n_m = 0.1. For the stopping criteria, we use large numbers and test these for a several runs. We compared the performance of the GA to the MIP results and increased the G and BSR when we were not satisfied. We yielded acceptable results using a G of 3000 and a BSR of 1000. With these settings, each run takes around 5 minutes.

We then ran the all five scenarios, same as in the MIP process. However, the GA is a stochastic process since it is dependent on randomness to generate the first generation. Hence, we run each scenario 10 times, the average results of which are shown below in Table 5-3. This table also shows the gap between the MIP results and the GA results. The gaps are calculated for all objectives but are shown in grey if they are not included in the objective of that scenario. The gaps below 0% (highlighted in green) indicate the GA found a better solution than the MIP. As can be seen in Table 5-3, the performance gap of the GA compared to the MIP is at most 5% for all the included objectives. All the GA runs in total took 4.5 hours, whereas the MIP results took 22.5 hours in total. Looking at the combined objective runs in scenarios 4 and 5, the total time spent by the GA was 60 and 54 minutes, respectively, and the MIP spent 20,000 seconds on each (approx. 5.5 hours). Thus, we believe that for larger problem instances, it is more time-efficient to use the GA to solve our Ergo-MMALBP without risking yielding unsatisfactory results. Moreover, GA is more suitable to apply multi-objective optimisation, which would be the next step of the GA automated balancing method. The full results of the GA runs can be found in Appendix I.

Table 5-3. Averaged GA results and gap to MIP

Scenario	MIP			GA[a]			Gap[b]		
	CT	SUM	MAX	CT	SUM	MAX	CT	SUM	MAX
1 (CT)	112.00	9.018	3.895	112.87	9.009	3.738	0.8%	-0.1%	-4.0%
2 (SUM)	205.38	6.794	3.359	331.58	5.023	3.023	61.4%	-26.1%	-10.0%
3 (MAX)	182.60	7.001	3.001	233.26	6.976	3.002	27.7%	-0.4%	0.0%
4 (CT & SUM)	112.78	8.991	3.728	112.50	9.011	3.676	-0.3%	0.2%	-1.4%
5 (CT & MAX)	112.20	9.003	3.136	114.04	9.020	3.293	1.6%	0.2%	5.0%

[a]The results shown are the average of 10 runs of each scenario
[b]The gap is calculated as follows: (GAresult-MIPresult)/MIPresult

The fitness function used in the GA is equal to the objective function used for the MIP, see Section 5.3.1. Since we constructed and ran the MIP scenarios chronologically before the GA, we did not include the current knowledge of the upper bound of the CT being higher than 220 seconds. However, since any solution's CT being above 220 seconds would make the CT objective a value higher than 1, we do not believe it to be of influence on the best solutions found in each run of a scenario that includes the CT objective.

We now compare the performance of the GA's best solutions (lowest objective function value) in the combined objective scenarios with the performance of the MIP and manual results, as we also did for the MIP. Figure 5-14 shows all the results for the combination of the CT & SUM objectives, where the GA's results are added in pink. Confirming the gap discussed above, the GA does not perform as well as the MIP and thus is not on the pareto frontier. However, the GA result of scenario 4, the CT & SUM scenario, would shift the pareto frontier when compared solely to the manual results, see the pink pareto frontier. Figure 5-15 shows the results for the CT & MAX objective combination. Here we observe the similar, expected situation: the GA outperforms some of the manual results, but not the MIP. A difference here, however, is that in this case both GA results for scenario 4 and 5 are on the pareto frontier of the CT & MAX objectives.

We now move on to in the next chapter to consider the possibilities for implementation of all approaches explored in this research.

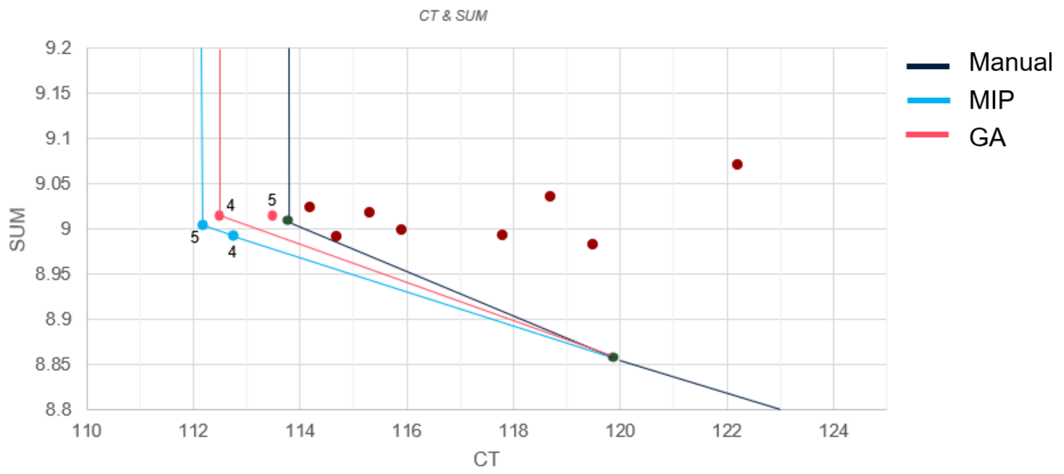

Figure 5-14. Pareto frontier of manual results, MIP and GA (CT & SUM)

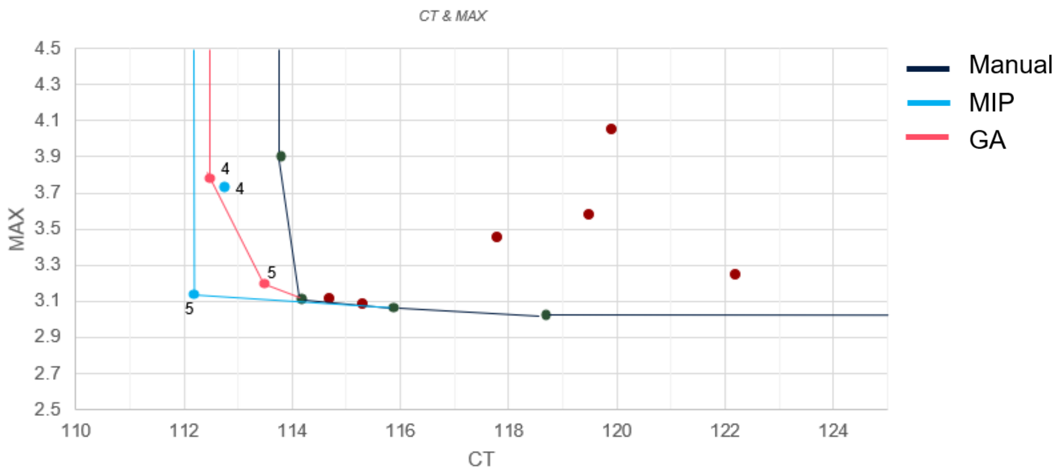

Figure 5-15. Pareto frontier of manual results, MIP and GA (CT & MAX)

5.4 Conclusions

This chapter explores the performance of approaches described in Chapter 4, when applied to the pedal car test case. This case is a simplification of truck assembly reality, but we argue it is a valid starting point for exploring approaches to include ergonomics into the balancing process. To assess he manual approach, we conducted experiment with process engineers. These process engineers provided results that show the inclusion of ergonomic data from the start is an ergonomic improvement compared to the current situation. In the case of comparing initial balance results, it is a significant improvement for both peak reduction and overall reduction of ergonomic risks. When comparing the results with ergonomic feedback to the results where ergonomic data was available, we see the latter performs significantly better in peak reduction.

We also assess the results of the automated approaches. Compared to the manual approach, the MIP results show they perform better on both CT and ergonomic objectives. The MIP results are not optimal, though, since the time-cap cut off the optimization process after 5.5 hours. Next, the GA performance is measured by taking the average of 10 runs, due to the stochastic nature of the GA algorithm. We compare these results to the MIP results and conclude that the GA appears to be an acceptable metaheuristic approach based on the gap to the MIP results. Overall, however, the GA's best runs do not obtain better objective values for CT and ergonomics than the MIP results, but obtain their results in only approximately 6 minutes per run. We conclude the GA has a better performance in terms of time, but the MIP performs better on the objectives put into both models.

6 Implementation plan

The pedal car test case was used to test the feasibility, functionality and performance of the model. Subsequently, the question arises: "How can the best performing approach for the pedal car test case be implemented in Scania's truck assembly line balancing process?". In this chapter, we answer this question by describing the translation from pedal car test case to Scania's truck assembly line (Section 6.1) and the expected performance of the approaches (Section 6.2). Finally, we provide a roadmap in Section 6.3 to explore which steps must be taken in which timeframe to realise implementation.

6.1 Translation from pedal car test case to truck assembly

Where we described the differences between the PCTC and the truck assembly in Section 5.1, we now look at the possibilities. While we successfully explored manual and automated approaches with the PCTC, there are different roads to be taken to 'reach' the truck assembly maturity level. Hence, we discuss the three areas of research separately: data gathering, manual approach and automated approaches.

First, we explore the options of implementing the data gathering methodology. The software programs AviX and IMMA are developed now to support the REBA assessments and the data transfers of the REBA scores from one program to the other. One development that is currently in progress is the realisation of an ergonomic score visualisation in the AviX balancing chart. The time-weighted average REBA score is currently shown in a separate window in AviX, making it more cumbersome to check what certain changes in task distribution do to the scores.

The collaboration with both the AviX and IMMA developers was very successful and both are planning to include the Scania Ergonomic Standard (SES) as the ergonomic assessment method or have already done so. Therefore, the use of the AviX-IMMA connection for ergonomic data gathering to balance the truck assembly line seems only a small step. While this is true in a sense, Scania has yet to explore the validity of the IMMA simulated assessments of SES and compare it to the ergonomists assessments as they would be made now. Validation is thus a step that must succeed in order to implement the simulated ergonomic assessments. Similarly, the AviX software will need to find a way to aggregate the SES assessments per task, like it now does with the time-weighted average REBA score. Besides, the manual input form of the SES assessment will need to be included, to still allow for manual input. All in all, some adaptations need to be made to the data gathering process, but the willingness and progress of both software programs' developers make this a promising method.

Next, we explore the manual method of balancing including ergonomics. The PCTC is a simplified version of the truck assembly but in case of the manual approach, it contains most of the aspects a truck case does too: tasks with task times, variants codes (for different models) and, in this case, ergonomic scores. In Section 5.1 we mentioned several aspects that are not included in the PCTC. However, most are already incorporated by the process engineer in the current situation. The truck assembly tasks contain information about the location of operators and variant mix; the number of operators and variant workers, can be assigned by the process engineers themselves. While the number of tasks is significantly larger in the truck assembly case, the process engineers are assigned sections of the assembly line to balance.

However, one improvement that might be needed is the availability of precedence relations. Currently, the SAMS mentioned in Section 2.1 does have a general precedence, but this is not recorded on task-level. While communication with assembly line team leaders and operators is still desirable, it would not be required anymore, which can facilitate a quick balancing process. Finally, we believe using the ergonomic data in the balancing process will require some specific training of process engineers.

Overall, once the ergonomic data gathering is successful, the manual approach could be implemented fairly quickly.

Finally, we discuss the translation of the PCTC to truck assembly considering the automated methods. For the automated approaches (exact or metaheuristic) to be implemented in the truck assembly line, most of the differences mentioned in Section 5.1 (and shortly touched upon here) would need to be built into the model constraints and/or algorithms. Extra parameters or variables would be required to add multiple operators to a station and to assign work to those operators; even more aspects would need to be added if variant workers were added. Moreover, we did not come across any literature discussing such an all-encompassing model/algorithm. We can assume, however, that a metaheuristic would be recommended or even required for such complexity.

While this is theoretically all possible, the amount of data required as input would grow very large and, as mentioned, not all required data are currently stored in files. Thus, besides building a complex algorithm, the data gathering would be a considerable task. Possibilities to alleviate this burden might lie in using machine learning and/or historical data of previous balance results to find the precedence relations and zones of datasets, as used in the tool currently under development by Mr. Gebler at Volkswagen (M. Gebler, Industrial Engineer Volkswagen, personal communication, December 14, 2020), who references research from Klindworth et al. (2012) for finding precedence relations in historical data. Despite the possibilities for the future, we conclude that the automated method as discussed in this research is not yet mature enough for implementation in the truck assembly line balancing process.

6.2 Expected performance

Based on the conclusions in the previous section, we elaborate on the expected performance of the manual approach only; the automated approach's immaturity makes it impossible to predict its performance. If all conditions of implementation of the manual approach are met, we believe this approach can be very beneficial for Scania. Multiple stakeholders would benefit, and we expect implementation of inclusion of ergonomics in the assembly line balancing process to:

- reduce the number of work-related musculoskeletal disorders in **assembly line operators**.
    - reduce absenteeism, thus saving costs for **Scania.**
    - increase work satisfaction, thus yielding less turnover in workforce and saving training and education costs for **Scania.**
- reduce the time it takes **ergonomists** to ergonomically assess all stations, in general and specifically after a re-balancing activity.
- increase ergonomic awareness in **process engineers**.
- reduce the need for re-balancing activities due to bad ergonomics, saving time for **ergonomists** and **process engineers**.

Due to the small case application in this research and the unknown scale of the effects on truck assembly, we cannot make a valid estimation of the possible monetary benefits. We cannot predict how many musculoskeletal disorders it will prevent, either. We will, however, make an estimation of possible time savings in terms of ergonomic assessments.

Currently, an assessment of a position standard (PS) takes 4 hours (see Section 2.2.2). Of 79 tasks in the PCTC, we simulated 40 of them, taking us 11.5 hours, see details in Appendix J. The other 39 were simple tasks (see Section 4.1.1) and were manually assessed in approximately 30 minutes, making a total ergonomic assessment time of 12 hours. One could argue that, with these tasks being divided over 3 stations, this process took equally long as the current situation. However, the created ergonomic assessments of tasks can be re-used for future re-balancing activities and do not have to be re-assessed unless there are significant changes in posture. For the current situation, the assessment is made of a combination of tasks and when the combination of tasks changes, the PS assessment is not valid anymore. Thus, this new ergonomic assessment method would yield large time savings in the long run.

6.3 Roadmap

Recall that we assessed the practical applicability of both the manual and automated approaches explored in this thesis in Section 6.1. We now concretise the recommendations made using a roadmap for implementation, see Figure 6-1.

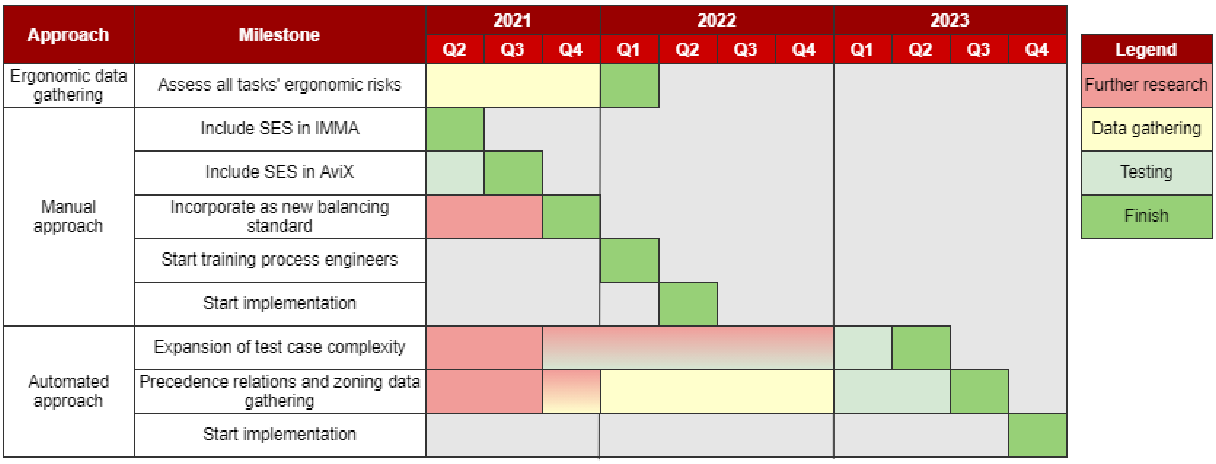

Figure 6-1. Roadmap for implementation

This roadmap shows for each of the approaches explored, which general steps can be taken in which estimated time frame to facilitate implementation. We go through them one by one. The ergonomic data gathering process is based on the task of ergonomically assessing all tasks. Due to the large size of this endeavour, we believe it will take some time to do this, but we expect this can be done in approximately one year.

For the manual approach, we believe the major steps are to include the Scania Ergonomic Standard (SES) in IMMA and AviX. Both these steps are already in progress at this moment. We expect these adaptations to be tested and done in the second and third quartile, respectively. Importantly, we expect some further research will be necessary to define the details of the new balancing standard: how are the tasks' ergonomic risk scores best aggregated, which station ergonomic scores are acceptable etc. Assuming full cooperation of all relevant stakeholders, we estimate this can be finished in Q4 of this year. Next, the training of process engineers can be rolled out, where they learn how to incorporate the ergonomic data in the balancing process. Finally, we estimate practical application of the manual approach should be feasible in Q2 of 2022.

For the automated approach, however, we believe the immaturity of this approach requires a much longer time frame. Optimistically, further research and testing of the approaches with more complex test cases can be done over the coming two years. Moreover, gathering the precedence relations and zoning data will also be a long-term project, in which we include researching the option of using machine learning and historical data. We also expect some testing and validation of the acquired data to be necessary. Overall, we expect the automated approach (exact or metaheuristic) to be ready for implementation in approximately 3 years' time.

7 Conclusions and recommendations

During this research, we aimed to develop a suitable and improved balancing process for Scania's assembly line, solving the problem of the suboptimal (i.e. single-objective and manual) balancing process including the aspect of ergonomics. To achieve this, we explored multiple aspects: the inclusion of simulated ergonomic assessments, the support for multi-objective manual balancing in the currently used software tool AviX, and the opportunities for automation of the balancing process. These aspects were derived from the core problems identified in the balancing process of Scania:

- ***Simulated ergonomic assessments are not incorporated into the balancing system***
- ***The currently used software tools do not support automation and multi-objective balancing***

We describe the conclusions in the next section and give recommendations in Section 7.2.

7.1 Conclusions

For the incorporation of simulated ergonomic assessments, we served as a test-user to the software developers of AviX and IMMA to achieve a connection between the two; thereby enabling the use of simulated ergonomics assessments in the balancing system. During this process, the currently used balancing tool AviX was also adapted to be able to view the ergonomics objective and manually assess the ergonomic risks involved in grouping certain tasks together. Thus, the new AviX version supports the multi-objective balancing we aim to do.

We tested this manual multi-objective method by conducting experiments with a variety of process engineers: from different manufacturing environments around the world, from within Scania and external. These experiments yielded good results in terms of decreased ergonomic risks, compared to the current situation: In the initial balance the process engineers reached significantly less ergonomically risky balancing results when including the ergonomic data using the new AviX version. When comparing the balancing with ergonomic data to the balancing with only ergonomic feedback, we also noted reduction in ergonomic risk peaks over the pedal car assembly line, when the ergonomic data is known to and visible for the process engineer. We can conclude that both the new version of AviX and the multi-objective manual balancing that is now possible are very promising balancing processes for the future.

The opportunities for automation of the balancing process are also explored but turn out to be less mature and ready for implementation. We explored both an exact method and a metaheuristic for solving our ergonomic mixed-model assembly line balancing problem with the aim to reduce cycle time (Ergo-MMALBP-II). The exact method was an expansion of an existing mixed integer program: a mathematical programming model built by the VF-KDO research project to find optimal solutions. However, since MMALBPs are NP-hard, we used it to explore possible lower bounds to our minimization problem and to estimate the performance of our genetic algorithm metaheuristic. In both methods, we explored the objectives of CT, peak ergonomic risk reduction and total ergonomic risk reduction. The combined objective scenarios consisted of combining CT and peak ergonomic risk reduction with equal weights of 50% and combining CT and total ergonomic risk reduction with equal weights of 50%.

While the MIP did not reach certain optimality in the combined objective scenarios – it was time-capped after 5.5 hours approximately – it yielded results that outperformed the manual experiment results in terms of cycle time and was on the pareto frontier of both objectives. The GA performance was measured in terms of optimality gap to the solution found by the MIP and in time. The gap between the included objectives of the MIP and the GA was at most 5%, while the GA took around 1 hour to run one scenario, and the MIP took 5.5 hours. The balancing results that were achieved in the GA underperformed the MIP results slightly but were still an improvement compared to the manual approach. Considering the automated approach of balancing, we recommend using a GA or a similar metaheuristic method for solving the balancing problem. Based on our test case, it performs almost just as well as an exact method, but in one fifth of the time.

Our final conclusions are based not only on the performance of our explored approaches on the pedal car test case, but also on their maturity and suitability for implementation in the truck assembly line. The ergonomic data gathering method is very close to maturity and requires few changes. The manual multi-objective balancing approach is also quite mature, in the sense that the currently used tools in balancing are very close to being suitable for this new process. We foresee many benefits from this manual multi-objective balancing approach and conclude that it is worthy of further developing and finetuning for implementation.

The automated approach for balancing with combined productivity and ergonomic objectives is still quite immature. Considering the complexity of truck assembly compare to the pedal car test case, this approach is far from being scalable, which is a big limitation. The overall conclusion concerning the explored automation is that more research is definitely necessary to introduce automated balancing into Scania's truck assembly line balancing process.

7.2 Recommendations

Drawing from the research done and the conclusions above, we have the following recommendations considering assembly line balancing including ergonomics:

- Start the process for preparing implementation of the simulated ergonomic assessments and manual balancing approach.
    - Include SES in IMMA and AviX.
    - Validate the simulated ergonomic assessment methods.
    - Explore aggregation methods for tasks' SES scores; compute aggregated task scores into station scores (or work shift/takt time scores).
    - Explore the suggestion of an ergonomic aim/threshold
    - Explore the necessity of and options for ergonomic education for process engineers.
- Conduct further research on the automated Ergo-MMALBP-II approaches by including more realistic aspects such as multiple operators, multiple locations, variant workers and variant mix.
    - Explore options of gathering required data such as precedence relations from historical data, possibly based on or in cooperation with Volkswagen's research on this topic (see Section 6.1).
- Explore the options to solve such a large and complex case as the truck assembly line on smaller scale, such as a few stations at a time (areas).
- Consider ergonomics as an output of balancing, instead of an input as we did. Currently in VF-KDO and MOSIM research projects, research is being done into optimizing ergonomics as an output. Applying this to balancing would mean the ergonomics could change if tasks are combined in a station differently.

References

Abdous, M.-A., Delorme, X., Battini, D., Sgarbossa, F., & Berger-Douce, S. (2018). Multi-objective optimization of assembly lines with workers fatigue consideration. *IFAC PapersOnLine*, 698-703.

Akyol, S. D., & Baykasoğlu, A. (2019). ErgoALWABP: a multiple-rule based constructive randomized search algorithm for solving assembly line worker assignment and balancing problem under ergonomic risk factors. *Journal of Intelligent Manufacturing*, 291-302.

Alghazi, A., & Kurz, M. E. (2018). Mixed model line balancing with parallel stations, zoning constraints, and ergonomics. *Constraints*, 123-153.

Al-Zuheri, A., Luong, L., & Xing, K. (2016). Developing a multi-objective genetic optimisation approach for an operational design of a manual mixed-model assembly line with walking workers. *Journal of Intelligent Manufacturing*, 1049-1065.

Barathwaj, N., Raja, P., & Gokulraj, S. (2015). Optimization of assembly line balancing using genetic algorithm. *Journal of Central South University*, 3957-3969.

Battini, D., Delorme, X., Dolgui, A., & Sgarbossa, F. (2015). Assembly line balancing with ergonomics paradigm- two alternative methods. *IFAC PapersOnLine*, 586-591.

Battini, D., Delorme, X., Dolgui, A., Persona, A., & Sgarbossa, F. (2016). Ergonomics in assembly line balancing based on energy expenditure: a multi-objective model. *International Journal of Production Research*, 824-845.

Baykasoğlu, A., & Özbakır, L. (2007). Stochastic U-line balancing using genetic algorithms. *The International Journal of Advanced Manufacturing Technology*, 139-147.

Botti, L., Mora, C., & Regattieri, A. (2017). Integrating ergonomics and lean manufacturing principles in a hybrid assembly line. *Computers & Industrial Engineering*, 481-491.

Bukchin, J., Dar-El, E. M., & Rubinovitz, J. (2002). Mixed model assembly line design in a make-to-order environment. *Computers & Industrial Engineering*, 405-421.

Cakir, B., Aliparmak, F., & Dengiz, B. (2011). Multi-objective optimization of a stochastic assembly line balancing: A hybrid simulated annealing algorithm. *Computers & Industrial Design*, 376-384.

Cambridge Dictionary. (n.d.). *Cambridge Dictionary*. Retrieved October 9, 2020, from https://dictionary.cambridge.org/dictionary/english/ergonomics

Carnahan, B. J., Norman, B. A., & Redfern, M. S. (2001). Incorporating physiscal demand criteria into assembly line balancing. *IIE transactions*, 875-887.

Carnahan, B. J., Norman, B. A., & Redfern, M. S. (2001). Incorporating physiscal demand criteria into assembly line balancing. *IIE Transactions*, 875-887.

Cheshmehgaz, H. R., Haron, H., Kazemipour, F., & Desa, M. I. (2012). Accumulated risk of body postures in assembly line balancing problem and modeling through a multi-criteria fuzzy-genetic algorithm. *Computers & Industrial Engineering*, 503-512.

Di Benedetto, R., & Fanti, M. (2012). An integrated tool to support engineers for WMSDs risk assessment during the assembly line balancing. *Work* , 2329-2333.

Fathi, M., Fontes, D. B., Moris, M., & Ghobakhloo, M. (2018). Assembly line balancing problem: A comparative evaluation of heuristics and a computational assessment of objectives. *Journal of Modelling in Management*, 455-474.

Fathi, M., Nourmohammadi, A., Ng, A. H., & Syberfeldt, A. (2019). An Optimization Model for Balancing Assembly Lines With Stochastic Task Times and Zoning Constraints. *IEEE, 7*, 32537-32550.

Fathi, M., Nourmohammadi, A., Ng, A. H., & Syberfeldt, A. (2020). An improved genetic algorithm with variable neighborhood search to solve the assembly line balancing problem. *Engineering Computation*, 501-521.

Finco, S., Battini, D., Delorme, X., Persona, A., & Sgarbossa, F. (2020). Workers' rest allowance and smoothing of the workload in assembly lines. *International Journal of Production Research*, 1255-1270.

Gosh, S., & Gagnon, R. J. (1989). A comprehensive literature review and analysis of the design, balancing and scheduling of assembly systems. *Inernational Journal of Production Research*, 637-670.

Hanson, L., Högberg, D., & Söderholm, M. (2012). Digital test assembly of truck parts with the IMMA-tool - an illustrative case. *Work: A Journal of Prevention, Assessment and Rehabilitation*, 2248-2252.

Hanson, L., Sperling, L., Gard, G., Ipsen, S., & Olivares Vergara, C. (2009). Swedish anthropometrics for product and workplace design. *Applied Ergonomics*, 797-806.

Hignett, S., & McAtamney, L. (2000). Rapid Entire Body Assessment (REBA). *Applied Ergonomics*, 201-205.

Holland, J. (1975). *Adaptation in natural and artificial systems.* Ann Arbor, Michigan: University of Michigan Press.

Kara, Y., Atasagun, Y., Gökçen, H., Hezer, S., & Demirel, N. (2014). An integrated model to incorporate ergonomics and resource restrictions into assembly line balancing. *International Journal of Computer Integrated Manufacturing*, 997-1007.

Karhu, O., Kansi, P., & Kuorinka, I. (1977). Correcting working postures in industry: a practical method for analysis. *Applied Ergonomics*, 199-201.

Klindworth, H., Otto, C., & Scholl, A. (2012). On a Learning Precedence Graph Concept for the Automotive Industry. *European Journal of Operational Research*, 259-269.

Koningsveld, E., Dul, J., Van Rhijn, G., & Vink, P. (2005). Enhancing the impact of ergonomics interventions. *Ergonomics, 48*(5), 559-580.

Li, G., & Buckle, P. (1999). *Evaluating change in exposure to risk for musculoskeletal disorders: A practical tool.* Suffolk, England: HSE Books.

Lowe, B. D., Dempsey, P. G., & Jones, E. M. (2019). Ergonomics assessment methods used by ergonomics professionals. *Applied Ergonomics, 81*, 102882.

Man, K., Tang, K., & Kwong, S. (1999). *Genetic Algorithms Concepts and Design.* London; New York: Springer.

Manavizadeh, N., Rabbani, M., Moshtaghi, D., & Jolai, F. (2012). Mixed-model assembly line balancing in the make-to-order and stochastic environment using multi-objective evolutionary algorithms. *Expert Systems with Applications*, 12026-12031.

McAtamney, L., & Corlett, E. (1993). RULA: a survey method for the investigation of work-related upper limb disorders. *Applied ergonomics*, 91-99.

McAtamney, L., & Hignett, S. (1995). REBA- A Rapid Entire Body Assessment Method for Investigating Work Related Muskuloskeletal Disorders. *Proceedings of Ergonomics Society of Australie Conference.* Glenelg.

MOSIM. (2018). *Poject*. Retrieved from MOSIM.eu: https://mosim.eu/project.html

Mura, M. D., & Dini, G. (2019). Optimizing ergonomics in assembly lines A multi objective genetic algorithm. *CIRP Journal of Manufacturing Science and Technology*, 31-45.

Mura, M. D., & Dini, G. (2019). Optimizing ergonomics in assembly lines: A multi objective genetic algorithm. *CIRP Journal of Manufacturing Science and Technology*, 31-45.

Nilakantan, J. M., & Ponnambalam, S. (2016). Robotic u-shaped assembly line balancing using particle swarm optimization. *Engineering Optimization*, 231-252.

Nourmohammadi, A., Fathi, M., Zandieh, M., & Ghobakhloo, M. (2019). A Water-Flow Like Algorithm for Solving U-Shaped Assembly Line Balancing Problems. *IEEE Access*, 129824-129833.

Nourmohammadi, Fathi, & Ng. (2020). *Line balancing optimization in pedal car assembly line of Scania: Mathematical approach.* Skövde: Internal document.

Nunes, I. L., & Cruz Machado, V. (2007). Merging Ergonomic Principles into Lean Manufacturing. *Proceedings of the 2007 Industrial Engineering Research Conference.*

Occhipinti, E. (1998). OCRA: a concise index for the assessment of exposure to repetitive movements of upper limb ergonomics. *Ergonomics*, 1290-1311.

Otto, A., & Scholl, A. (2011). Incorporating ergonomic risks into assembly line balancing. *European Journal of Operational research*, 277-286.

Polat, O., Mutlu, Ö., & Özgormus, E. (2018). A Mathematical Model For Assembly Line Balancing Problem Type 2 Under Ergonomic Workload Constraint. *The Ergonomics Open Journal*, 1-10.

Rader, Jr., D. J. (2010). *Deterministic Operations Research.* Hoboken, New Jersey: John Wiley & Sons Inc.

Scania. (2020). *Scania configurator Nederland*. Retrieved 8 11, 2020, from Scania configurator: https://configurator.scania.com/index.aspx?etel_market=5137&etel_language=5229

Scania AB. (2018). *Our Modular System*. Retrieved from Scania.com: https://www.scania.com/group/en/home/about-scania/scania-in-brief/how-we-create-value/our-modular-system.html

Scania AB. (2019). *Annual and Sustainability Report.* Södertälje, Sweden.

Scania AB. (2019). *Smart Labs*. Retrieved 05 26, 2020, from Scania.com: https://www.scania.com/group/en/home/about-scania/innovation/research/smart-labs.html

Schaub, K., Caragnano, G., Britzke, B., & Bruder, R. (2010). The European assembly worksheet. *Proceedings of the eighth international conference on occupational risk prevention.* Valencia, Spain.

Sheskin, D. J. (2000). *Handbook of Parametric and Nonparametric Statistical Procedures.* Boca Raton, Florida: Chapman & Hall / CRC.

Slack, N., Brandon-Jones, A., & Johnston, R. (2016). *Operations Management* (8th edition ed.). Harlow: Pearson Education Limited.

Theisens, H. (2016). *Lean Six Sigma Green Belt - Mindset, skill set and tool set.* Amstelveen: Lean Six Sigma Academy.

Thomopoulos, N. T. (1967, October). Line Balancing-Sequencing for Mixed-Model Assembly. *Management Science, 14*, B59-B75.

VF-KDO. (2019). *About VF-KDO*. Retrieved from VF-KDO - Virtual Factories with Knowledge Driven Optimisation: https://www.virtualfactories.se/about

Waters, T. R., Putz-Anderson, V., & Carg, A. (1994). Applications manual for the revised NIOSH lifting equation. *NIOSH Publication No. 94-110*.

Wickens, C. D., Gordon, S. E., & Liu, Y. (1998). *An introduction to human factors engineering.* New York: Longman.

Winston, W. L. (2004). *Operations Research.* Belmont, USA: Brooks/Cole - Thomson Learning.

Yuan, B., Zhang, C., & Shao, X. (2015). A late acceptance hill-climbing algorithm for balancing two-sided assembly lines with multiple constraints. *Journal of Intelligent Manufacturing*, 59-168.

Appendix A. Questionnaires participants

This appendix contains the questionnaires filled in by the participants both before (A.1) and after (A.2) conducting the experiments, as referred to in Section 4.2.

A.1 Before conducting experiments

We distinguish between an internal questionnaire, for participants from Scania, and an external questionnaire, for participants from other companies.

Internal questionnaire

Questions marked with * are required.

Personal information

This information will not be shared with anyone, but will be used to distinguish between results.

1. Name*
2. Country*
3. Area of expertise*
4. Scania Department*

Experience & knowledge

These questions provide insight into the level of knowledge and experience you as a participant had before starting the experiments.

5. How many years have you worked with AviX?* - *Answer is limited to numbers*
6. How would you rate your knowledge of AviX?* - *Answer is limited to 1, 2, 3, 4, or 5 stars*
7. What is your experience with AviX? (A short description, for example containing type of operations you do/did in AviX, etc.)*
8. How many years have you worked with assembly line (workload) balancing?* - *Answer is limited to numbers*
9. How would you rate your knowledge of assembly line (workload) balancing?* - *Answer is limited to 1, 2, 3, 4, or 5 stars*
10. What is your education in assembly line (workload) balancing?* - *Answer options are: None, Basic training, BSc including balancing, MSc including balancing, PhD / Specialisation beyond MSc, Other: [text field] .*
11. What is your experience with assembly line (workload) balancing activities? (A short description, for example containing type of assembly line, etc.)*
12. How many years of experience do you have with ergonomics* - *Answer is limited to numbers*
13. How would you rate your knowledge of ergonomics?* - *Answer is limited to 1, 2, 3, 4, or 5 stars*
14. What is your education in ergonomics?* - *Answer options are: None, Basic training, BSc including ergonomics, MSc including ergonomics, PhD / Specialisation beyond MSc, Other: [text field] .*
15. What is your current knowledge of / experience with ergonomics? (A short description, for example containing type of assembly line, etc.)*
16. How would you describe the current assembly line balancing process (to your knowledge)?*
17. What are your thoughts on the current assembly line balancing process? (If your answer to this question is used in any way in reports or presentations, it will be anonymized)*

External questionnaire

Questions marked with * are required.

Personal information

This information will not be shared with anyone, but will be used to distinguish between results.

1. Name*
2. Country*
3. Company*
4. Job title*
5. Area of expertise*

Experience & knowledge

These questions provide insight into the level of knowledge and experience you as a participant had before starting the experiments.

6. How many years have you worked with AviX?* - *Answer is limited to numbers*
7. How would you rate your knowledge of AviX?* - *Answer is limited to 1, 2, 3, 4, or 5 stars*
8. What is your experience with AviX? (A short description, for example containing type of operations you do/did in AviX, etc.)*
9. How many years have you worked with assembly line (workload) balancing?* - *Answer is limited to numbers*
10. How would you rate your knowledge of assembly line (workload) balancing?* - *Answer is limited to 1, 2, 3, 4, or 5 stars*
11. What is your education in assembly line (workload) balancing?* - *Answer options are: None, Basic training, BSc including balancing, MSc including balancing, PhD / Specialisation beyond MSc, Other: [text field] .*
12. What is your experience with assembly line (workload) balancing activities? (A short description, for example containing type of assembly line, etc.)*
13. How many years of experience do you have with ergonomics* - *Answer is limited to numbers*
14. How would you rate your knowledge of ergonomics?* - *Answer is limited to 1, 2, 3, 4, or 5 stars*
15. What is your education in ergonomics?* - *Answer options are: None, Basic training, BSc including ergonomics, MSc including ergonomics, PhD / Specialisation beyond MSc, Other: [text field] .*
16. What is your current knowledge of / experience with ergonomics? (A short description, for example containing type of assembly line, etc.)*

A.2 After conducting experiments

Name

This will not be used in any publication and statistics will be based on test subjects as group

1. Name*

Experiments

What did you think?

2. Please provide your feedback on the following statements:* - *Answers are Likert scale: Bad/Mediocre/Good*

    a. Clarity of explanation (introduction)
    b. Clarity of dataset
    c. Clarity of assignment
    d. Level of support (on content)
3. Please provide your feedback on the following statements:* - *Answers are Likert scale: Too short/Just right/Too long*
    a. The time scheduled for the introduction meeting
    b. The time to complete the experiment A1
    c. The time to complete the experiment A2
    d. The time to complete experiment B
4. What did you think of the first experiment (A1 & A2)?*
5. What did you think of the second experiment (B)?*
6. You received your own performance on these experiments. When comparing your results from experiment A with experiment B, what do you think? Consider both cycle time, ergonomics and time to perform the task.*
7. What do you think of including ergonomics in the balancing process in this way?*
8. Do you have any suggestions on how to include ergonomics in the balancing process?*
9. Any other comments?*

Appendix B. Adapted MIP model

This appendix contains the full MIP model (after adaptation) as referred to in Section 4.3.1. Table B-1 provides the indices, parameters and decision variables, after which the model itself is shown.

Table B-1. Model indices, parameters and decision variables

Indices:	
$\boldsymbol{i}$	Task index (i=1,…,nt); nt=number of tasks
$\boldsymbol{j}$	Station index (j=1,…,ns); ns= number of stations
$\boldsymbol{m}$	Model index (m=1,…,nm); nm=number of models
Parameters:	
$\boldsymbol{p_{hi}} \in (\mathbf{0},\mathbf{1})$	1 if task h is an immediate predecessor of task i; 0 otherwise
$\boldsymbol{s_{hi}} \in (\mathbf{0},\mathbf{1})$	1 if task h is an immediate successor of task i; 0 otherwise
$\boldsymbol{psall_{hi}} \in (\mathbf{0},\mathbf{1})$	1 if task h is an immediate predecessor or successor of task i; 0 otherwise
$\boldsymbol{zcp_{hi}} \in (\mathbf{0},\mathbf{1})$	Positive zoning constraint between task h and i
$\boldsymbol{zcn_{hi}} \in (\mathbf{0},\mathbf{1})$	Negative zoning constraint between task h and i
$\boldsymbol{t_{im}} \in \boldsymbol{R}$	Time of task i for model m
$\boldsymbol{Reba_i} \in \boldsymbol{R}$	Reba score of task *i*
Decision variables:	
$\boldsymbol{X_{ij}} \in (0,1)$	1 if task i is assigned to station j; 0, otherwise
$\boldsymbol{U_{hi}} \in (0,1)$	1 if task h is performed before task i; 0, otherwise
Dependent decision variables:	
$\boldsymbol{CT} \in$ Real	Cycle time
$\boldsymbol{C_{im}} \in$ Real	Completion time of task i for model m
$\boldsymbol{E_{jm}} \in$ Real	Average Reba score of model *m* in station *j*
$\boldsymbol{SE_j} \in$ Real	Maximum Reba score for station *j*
$\boldsymbol{SE_{max}} \in$ Real	Maximum Reba score
$\boldsymbol{Z_{ijm}} \in$ Real	Intermediate variable for linear notation

$$Min\ \ OF = \alpha \frac{CT - CT_{min}}{CT_{max} - CT_{min}} + \beta \frac{\sum_j SE_j - (\sum_j SE_j)_{min}}{(\sum_j SE_j)_{max} - (\sum_j SE_j)_{min}} + \gamma \frac{SE_{max} - (SE_{max})_{min}}{(SE_{max})_{max} - (SE_{max})_{min}}$$

s.t.

$$\sum_j X_{ij} = 1;\ \forall i \tag{1}$$

$$\sum_j j\ \times X_{hj} \leq \sum_j j\ \times X_{ij}\,;\ \forall (h,i)|p_{hi} = 1 \tag{2}$$

$$C_{hm} - C_{im} + M(1 - X_{ij}) + M(1 - X_{hj}) \geq t_{im};\ \forall (h,i)|p_{hi} = 1, \forall j, \forall m \tag{3}$$

$$C_{hm} - C_{im} + M(1 - X_{hj}) + M(1 - X_{ij}) + M(1 - U_{hi}) \geq t_{hm};\ \forall (h,i)|psall_{hi} = 0, \forall j, \forall m \tag{4}$$

$$C_{im} - C_{hm} + M(1 - X_{hj}) + M(1 - X_{ij}) + M(U_{hi}) \geq t_{im};\ \forall (h,i)|psall_{hi} = 0, \forall j, \forall m \tag{5}$$

$$C_{im} \leq CT;\ \forall\ i, \forall m \tag{6}$$

$$C_{im} \geq t_{im};\ \forall\ i, \forall m \tag{7}$$

$$X_{hj} = X_{ij};\ \forall (h,i)|zcp_{hi} = 1, \forall j \tag{8}$$

$$X_{hj} + X_{ij} = 1;\ \forall (h,i)|zcn_{hi} = 1, \forall j \tag{9}$$

$$\sum_{i=1}^{nt} Z_{ijm} \times t_{im} = \sum_{i=1}^{nt} X_{ij} \times t_{im} \times Reba_i\ ;\ \forall j, \forall m \tag{10}$$

$$Z_{ijm}\ \leq M \times\ X_{ij}\ ;\ \forall i, \forall j, \forall m \tag{11}$$

$$Z_{ijm}\ \leq\ E_{jm}\ ;\ \forall i, \forall j, \forall m \tag{12}$$

$$Z_{ijm}\ \geq E_{jm} - M\left(1 - X_{ij}\right);\ \forall i, \forall j, \forall m \tag{13}$$

$$SE_j \geq E_{jm}\ ;\ \forall j, \forall m \tag{14}$$

$$SE_{max} \geq SE_j\ ;\ \forall j \tag{15}$$

$$Z_{ijm}\ \geq 0\ ;\ \forall i, \forall j, \forall m \tag{16}$$

Equation 1 defines each task must be assigned to a station. Equation 2 ensures that precedence relations are respected. The completion time is defined by equation 3 in case of precedence relations, and by 4 and 5 in case there are no precedence relations, ensuring tasks on the same station do not overlap. Equation 6 sets the CT to the highest completion time, and equation 7 ensures the completion time encompasses a task's entire task time. Equations 8 and 9 ensure zoning constraints are adhered to, positive and negative respectively. Equations 10, 11, 12 and 13 define the stations' REBA score, as described above. Equation 14 assigns the highest REBA score of all models in one station as the station's REBA score. Finally, equation 15 does the same over all stations. The value M is a big number, the value of which can be found in Section 5.3.1.

Appendix C. Manual experiment participants

This appendix contains the information concerning the participants of the manual experiments, the results of which are described in Section 5.2.2. First, we provide the invitation with which the participants were approached in Appendix C.1, as referred to in Section 5.2.1. Next, the responses to the before questionnaire as shown in Appendix A.1, are gathered in Appendix C.2. This is referred to in Section 5.2.1. Finally, we aggregate the responses to the after questionnaire as shown in Appendix A.2 and provide them in Appendix C.3, which we refer to in Section 5.2.3.

C.1. Invitation

The participants were invited via e-mail, and responded to the following invitation (while wording may have varied, the requirements and content were the same for all):

"My name is Janneke and I am currently doing my master thesis project at the Smart Factory Lab in Södertälje. My thesis is about the (final) assembly line balancing process and including ergonomics in this process. For this, I will be doing some experiments with process engineers and/or people who are (or were recently) in practice responsible for balancing the tasks on the assembly line. The experiments consist of a small balancing activity: Dividing approx. 30 (clusters of) tasks over three stations, taking into account specific objectives defined in the experiment explanation. There is no need for physical presence in the lab (covid-safe), these experiments will be done digitally.

The requirements for respondents are:

- *Some knowledge of / experience with AviX*
- *Knowledge of and preferably experience with assembly line balancing*

Do you fit the requirements and are you willing to be one of the respondents? Or do you know names of suitable respondents for these experiments? Please let me know!"

C.2. Before-questionnaire

The following responses were given to the before-questionnaire. The answers to the questions concerning years of experience (questions 5, 8 & 12 for internal, 6, 9 & 13 for external) are summarized in the table below.

Table C-1. Years of experience

Years	AviX	Balancing	Ergonomics
0 to 2	3	4	10
3 to 5	5	2	1
6 to 10	3	4	1
11+	2	3	1

The questions concerning rating your own knowledge (questions 6, 9 & 13 for internal, 7,10 & 14 for external) are answered as follows:

Table C-2 Average self-rated knowledge

Topic	Average score
AviX	3.62
Balancing	3.85
Ergonomics	2.31

The questions concerning education (questions 10 & 14 internal, 11 & 15 external) yielded the following answers:

Table C-3. Level of education

Education Balancing	Number of participants
None	2
Basic training	6
BSc including balancing	1
MSc including balancing	1
Other	3
Education Ergonomics	**Number of participants**
None	4
Basic training	7
BSc including ergonomics	1
MSc including ergonomics	0
Other	1

Finally, the answers to the questions concerning a description of the experiences (questions 7, 11 & 15 internal, 8, 12, 16 external) were aggregated, as shown in the table below. The table indicates a general function/statement and the value indicates the frequency of such a function statement (in similar wording) being mentioned by a participant. One participant may be counted in multiple statements.

Table C-4. Description of experience

Experience AviX	
Using	12
Teaching / coaching	4
Developing	3
Experience line balancing	
Operational line balancing	11
Teaching / training	1
Developing methods	3
Experience ergonomics	
Common understanding	13
Understanding of specific ergonomic standards (e.g. SES)	7
Applied ergonomic standards (e.g. SES)	5
Former work experience in ergonomics field	1

C.3. After-questionnaire

The following responses were given to the after-questionnaire. The following table represents the answers given to questions 2 and 3:

Table C-5. Experiments clarity and time

	Question 2: Clarity				Question 3: Time			
	a. explanation	b. data	c. assignment	d. support	a. Intro	b. A1	c. A2	d. B
Good	12	9	10	12				
Mediocre	1	4	3	1				
Bad	0	0	0	0				
Too short					0	0	0	1
Just right					13	12	13	11
Too long					0	1	0	1

The following table represents the answers to questions 4, 5, 6 and 7. The table indicates a general statement and the value indicates the frequency of such a statement (in similar wording) being mentioned by a participant. One participant may be counted in multiple statements.

Table C-6. Opinions on experiments

Statement	*Frequency*
Question 4: A1 & A2	
Normal balancing procedure	6
Difficult to let go of usual reality-restrictions	3
Hard to work with provided precedence graph	3
Hard to work with unknown tasks	4
Question 5: B	
Interesting /useful method	8
Easy to work with	4
Difficult to include multi-objective aim	3
I do not have enough ergonomics knowledge	1
Question 6: compare A to B	
Longer CT but better ergo, as expected	3
Too long CT when including ergonomics	2
This is a good improvement / this method should be used	7
Question 7: including ergonomics this way	
We should incorporate this	9
This way is easier than current way (ergonomics-wise)	3
Multi objective balancing is harder than single objective	1

Question 8 requested suggestions from the participants on how to include ergonomics in the balancing process. We summarize the suggestions done in answering this question and the previous questions 6 and 7:

Table C-7. Suggestions on experiments

Suggestions how to include ergo	Question
Include variant mix	Q6

Include aim / suggestion value / threshold for ergonomic risk scores	Q6
Define costs of bad ergonomics	Q6
Calculate ergo on takt time, not on planned tasks (this way, idle time = resting = better ergonomics)	Q7
Include task rotation	Q7
Include more parameters	Q7
Include SES	Q8
➔ *Sequentially:* update AviX ergo scores when manual SES assessments are done	Q8
Include visual representation of ergonomic scores in balance chart	Q8
Investigate influence of workplace design	Q8
➔ *Sequentially:* separate product dependent tasks from workplace dependent tasks	Q8
Program STB & SAM codes in tasks with ergo from beginning if possible	Q8
Investigate effect of working a shift, not one takt	Q8

Appendix D. Manual approach experiment results

We provide the results of manual experiments A1, A2 and B in appendices D.1., D.2. and D.3., respectively. In D.4., we provide the pareto frontier graphs for all experiments. We refer to this appendix from Section 5.2.2.

D.1. Provided datasets

The following data is provided to the participants in AviX, first without the information in the REBA column (experiments A1 & A2), then with (experiment B). Below you find an overview of the AviX balance tree as the participants receive it. This same dataset is used for the automated approaches.

Table D-1. Dataset as used in experiments

Task Nr	Task description	Time black (s)	Time red (s)	REBA SCORE	Zone nr
1	START	0.0001	0.0001	1	1
2	Pick up front frame	6.5	8.6	4	2
3	Mount front frame	2.48	2.48	4	2
4	Go to material storage - steering column	4.3	4.3	1	3
5	Remove packaging from steering column	1.8	1.8	5	3
6	Go to pedal car	2.2	2.2	1	3
7	Mount steering column	3.6	3.6	7	3
8	Fetch clippers	1.6	0	1	4
9	Cut cable tie	4.9	0	4	4
10	Put away tool	1.6	0	1	4
11	Fetch screw and washer-rear of steering column	3.2	3.2	2	5
12	Mount rear screw of steering column	4.9	4.9	2	5
13	Tighten rear screw	7.1	7.1	4	5
14	Fetch screw and washer-front of steering column	4.3	4.3	2	6
15	Mount front screw of steering column	11.3	11.3	5	6
16	Fetch nuts and washers, 2pc	6.5	6.5	2	7
17	Mount nut and washer right steering link	7.2	7.2	2	7
18	Go to other side of pedal car	2.2	2.2	1	7
19	Mount nut and washer left steering link	5.6	5.6	2	7
20	Grasp powertool	2.2	2.2	4	8
21	Tighten left steering link screw	7.1	7.1	2	8
22	Put away tool	2.2	2.2	4	8
23	Grasp powertool	2.2	2.2	4	9
24	Go to other side of pedal car	2.2	2.2	1	9
25	Tighten right steering link screw	6	6	2	9
26	Put away wrench and powertool	3.2	3.2	4	9
27	Fetch torque wrench	2.7	2.7	1	10
28	Change angle of steering column, tighten front screw of steering column	7.7	7.7	4	10
29	Put away tool	1.6	1.6	1	10
34	Fetch screw, nut and washer	3.2	0	1	11
35	Enter screw in cap	9	0	8	11
36	Fetch tool	4.3	0	1	12

37	tighten screw in cap	23	0	8	12
38	fetch steering wheel screw and washer	5.9	5.9	1	13
39	mount steering wheel	21.2	21.2	3	13
40	fetch tool	1.1	1.1	1	14
41	tighten steering wheel	9	9	6	14
42	Put away tool	1.1	1.1	1	14
43	take rubber mallet	3.8	3.8	1	15
44	mount emblem	6	4	5	15
45	put away rubber mallet	1.1	1.1	1	15
46	Fetch front left wheel	1.6	1.6	1	16
47	Place front left wheel	1.8	1.8	1	16
48	Fetch front right wheel	5.4	5.4	1	17
49	Place front right wheel	1.8	1.8	1	17
50	Fetch screw and washer 1pc	2.7	2.7	1	18
51	Go to pedal car	3.8	3.8	1	18
52	Enter screw front right	3.3	3.3	1	18
53	Fetch screw and washer 1pc	2.7	2.7	1	19
54	Go to pedal car	2.2	2.2	1	19
55	Enter screw front left	3.3	3.3	1	19
56	Tighten front left wheel	6.1	6.1	5	20
57	Go to front right wheel	3.2	3.2	1	20
58	Tighten front right wheel	6.1	6.1	5	20
63	fetch a wheelhub cap	4.3	4.3	1	21
64	Go to rear left wheel	1.6	1.6	1	21
65	Mount a wheelhub cap	4.2	4.2	3	21
66	Bring back hammer	0.5	0.5	1	21
67	fetch a wheelhub cap	4.3	4.3	1	22
68	Go to front left wheel	1.6	1.6	1	22
69	Mount a wheelhub cap	2.4	2.4	2	22
70	Bring back hammer	0.5	0.5	1	22
71	fetch a wheelhub cap	4.3	4.3	1	23
72	Go to right left wheel	3.2	3.2	1	23
73	Mount a wheelhub cap	2.4	2.4	3	23
74	Bring back hammer	0.5	0.5	1	23
75	fetch a wheelhub cap	4.3	4.3	1	24
76	Go to rear right wheel	3.2	3.2	1	24
77	Mount a wheelhub cap	1.3	1.3	2	24
78	Bring back hammer	2.7	2.7	1	24
79	Read Mona	3.8	3.8	1	25
80	Mount washer on bracket	7.4	7.4	1	26
81	Go to pedal car	2.2	2.2	1	27
82	Place chair bracket	2.3	2.3	1	27
83	Fetch chair	3.2	3.2	3	28
84	Place chair on bracket	3.2	3.2	2	28
85	Fetch screw and torque wrench	6.8	6.8	1	29
86	Enter screw and tighten chair	13	13	3	29

87	Put away tool	1.1	1.1	1	29

Figure D-1. Balance tree in AviX

D.2. Results A1 and ergonomic feedback provided

Table D-2 below indicate the feedback given to each participant.

Table D-2. Manual experiments' results A1 and feedback

Time (mins)	CT	S1	S2	S3	SUM	MAX	Feedback

25	126.5	2.374	2.295	4.560	9.229	4.56	The ergonomic feedback I have is that the ergonomics in Station 3 is the worst of the three stations. Try to lower the ergonomics there by rearranging some of the tasks (Still according to the precedence diagram).
120	124.3	2.824	2.031	4.054	8.909	4.054	Your station 3 has worse ergonomics than stations 1 and 2. Station 2 has the best ergonomics. Try to improve the ergonomics in station 3 of your current balance.
90	123.6	3.010	2.239	4.036	9.285	4.036	The ergonomic workload of Station 3 is very high compared to the other stations. Try to make some adjustments to your initial balance, best you can, to include this feedback.
15	116.3	2.374	4.508	2.031	8.913	4.508	Your station 2 has the worst ergonomics of the three. Try to improve that by rearranging some tasks.
30	113.2	4.563	2.415	2.031	9.009	4.563	Station 1 currently has bad ergonomics (status orange). Try to make some adjustments to your initial balance, best you can, to include this feedback.
10	119.8	3.016	1.710	4.207	8.933	4.207	Currently, your Station 3 has the worst ergonomics. Your second station can take more ergonomic risk, to reduce the third station’s risk. Try to make some adjustments to your initial balance, best you can, to include this feedback
20	116.3	2.828	1.969	4.270	9.067	4.27	Currently, your Station 3 has the worst ergonomics. Your second station can take more ergonomic risk, to reduce the third station’s risk. Try to make some adjustments to your initial balance, best you can, to include this feedback
20	113.9	2.885	4.147	1.939	8.971	4.147	Station 2 has the worst ergonomics of the three, station 3 the best. Try to improve the ergonomic risk distribution.
30	112.5	2.642	4.041	2.340	9.023	4.041	Station 2 currently has the worst ergonomics. Second worst is station 1, and best is station 3. Try to rearrange tasks so that the ergonomic risks are better spread out.
37	116.4	2.993	2.850	3.181	9.024	3.181	Your station 3 has slightly worse ergonomics than stations 1 and 2.
75	113.2	2.667	3.932	2.415	9.014	3.932	Currently, station 3 has the highest (worst) ergonomic risk score. Try to rearrange the tasks to improve that.
75	117	2.903	1.938	4.275	9.116	4.275	Currently your station 3 has worst ergonomics of the three stations. Try to improve that by rearranging the tasks.
30	112.9	2.946	2.862	3.221	9.029	3.221	Station 3 currently has the worst ergonomics out of the three stations. For assignment A2, please try to incorporate this feedback by rearranging some tasks (even though you do not have any ergo data yet).

D.3. Results A2

Table D-3 below shows all the results of participants’ A2 experiments.

Table D-3. A2 results

Time (mins)	CT	S1	S2	S3	SUM	MAX
15	123.8	2.611	2.118	4.781	9.51	4.781
30	117.8	2.824	2.713	3.456	8.993	3.456
30	119.5	3.02	2.386	3.577	8.983	3.577
10	123.8	2.611	4.56	2.031	9.202	4.56

60	114.4	3.36	3.594	2.031	8.985	3.594
15	119.8	3.016	1.65	4.56	9.226	4.56
10	122.7	2.828	3.019	3.181	9.028	3.181
15	115.3	2.885	2.372	3.721	8.978	3.721
30	113.2	2.662	2.542	3.798	9.002	3.798
21	115.5	2.875	2.985	3.157	9.017	3.157
20	112.8	2.577	3.832	2.591	9.000	3.832
30	122.2	2.728	4.035	2.252	9.015	4.035
5	113.5	2.946	3.667	2.426	9.039	3.667

D.4. Results B

Table D-4 below shows the B experiment results of all participants.

Table D-4. B results

Time (mins)	CT	S1	S2	S3	SUM	MAX
20	175.3	3.54	3.264	2.031	8.835	3.54
30	117.8	2.824	2.713	3.456	8.993	3.456
30	119.5	3.02	2.386	3.577	8.983	3.577
5	175.3	3.54	3.264	2.031	8.835	3.54
60	113.8	2.798	2.315	3.896	9.009	3.896
30	119.9	2.734	2.074	4.05	8.858	4.05
30	115.3	3.017	3.088	2.913	9.018	3.088
15	146	2.885	3.535	2.183	8.603	3.535
75	114.7	3.091	3.116	2.785	8.992	3.116
17	118.7	3.02	3.015	3.001	9.036	3.02
30	115.9	3.065	2.887	3.047	8.999	3.065
30	122.2	2.728	3.098	3.245	9.071	3.245
50	114.2	2.882	3.036	3.106	9.024	3.106

D.5. Pareto frontiers

To show the performance of the participants in terms of CT and ergonomics, we display the scores and indicate the pareto frontier: the frontier of results that do best in terms of balancing the two objectives.

A1: Initial balancing

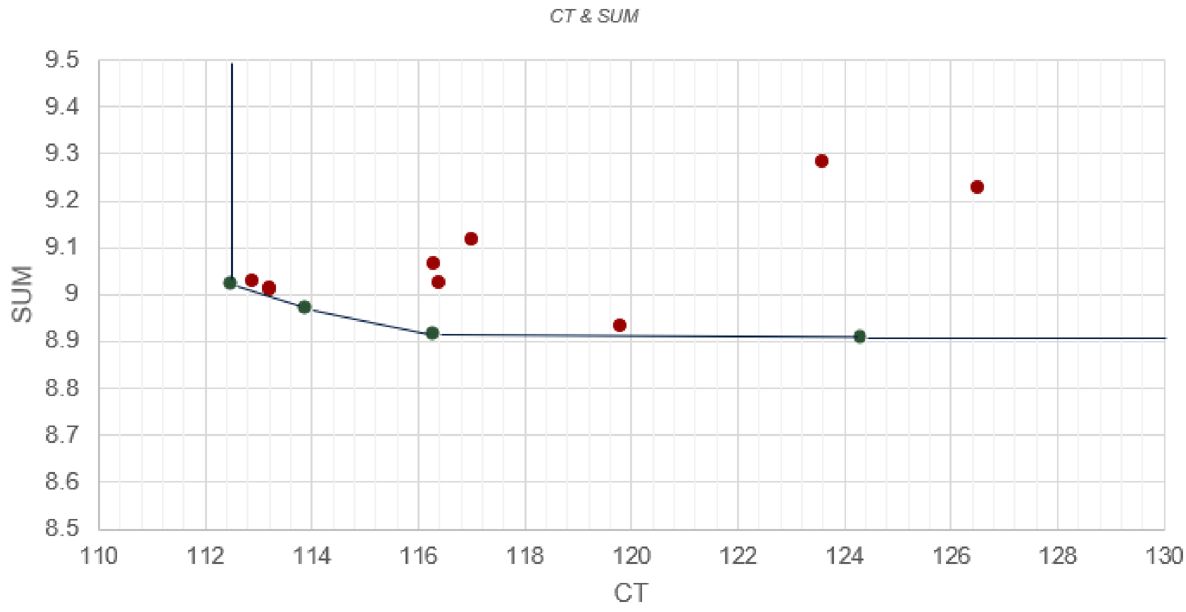

Figure D-2. A1: CT & SUM pareto frontier

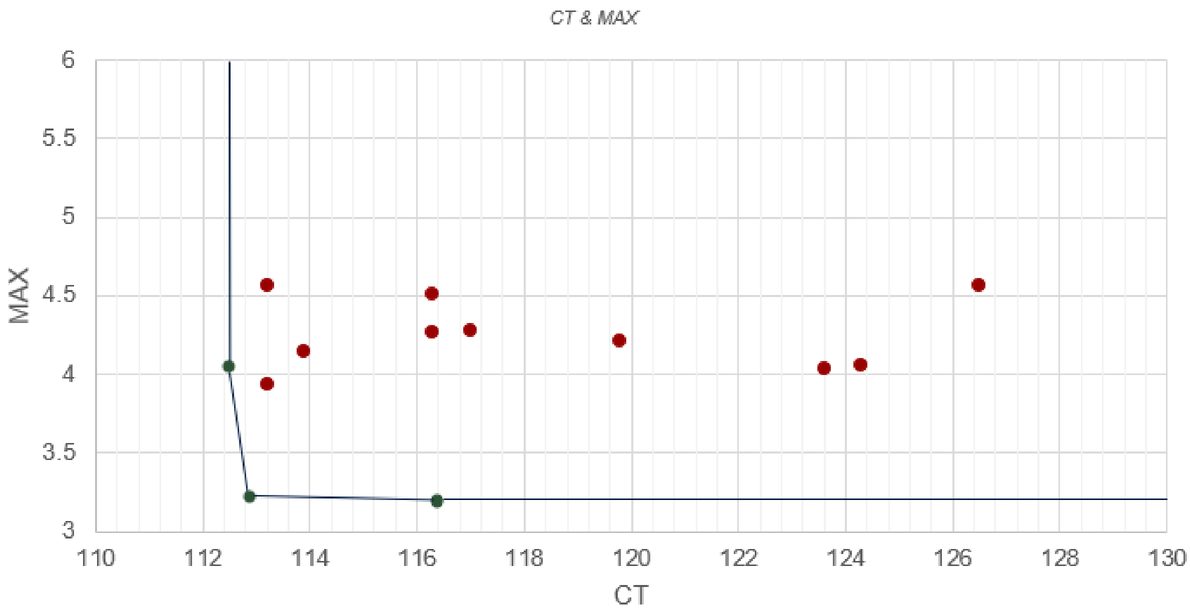

Figure D-3. A1: CT & MAX pareto frontier

A2: Including ergonomic feedback

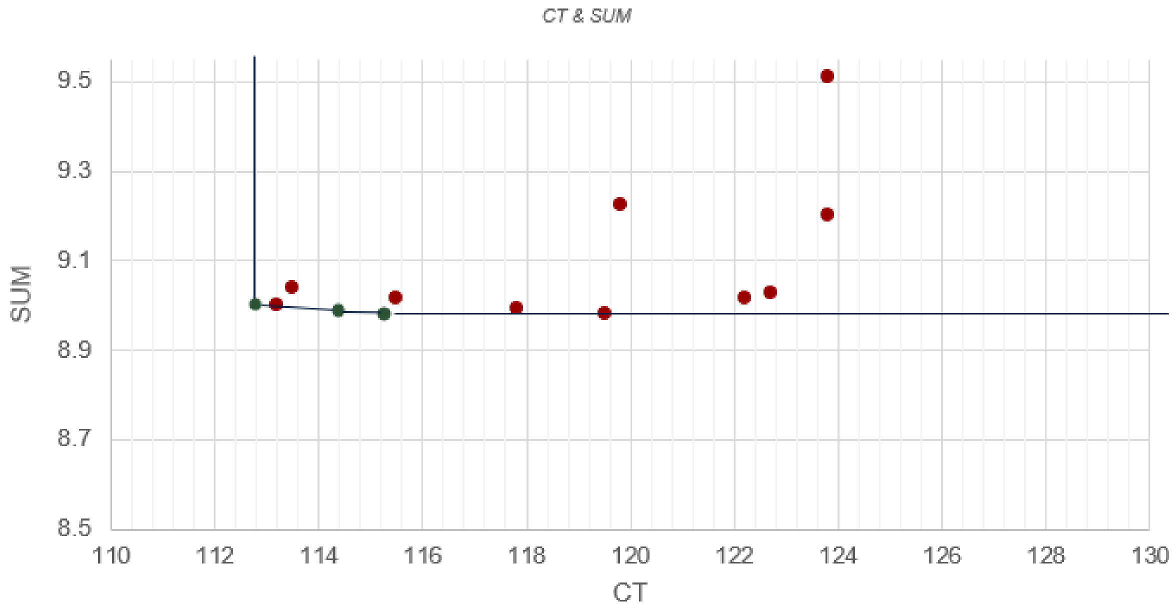

Figure D-4. A2: CT & SUM pareto frontier

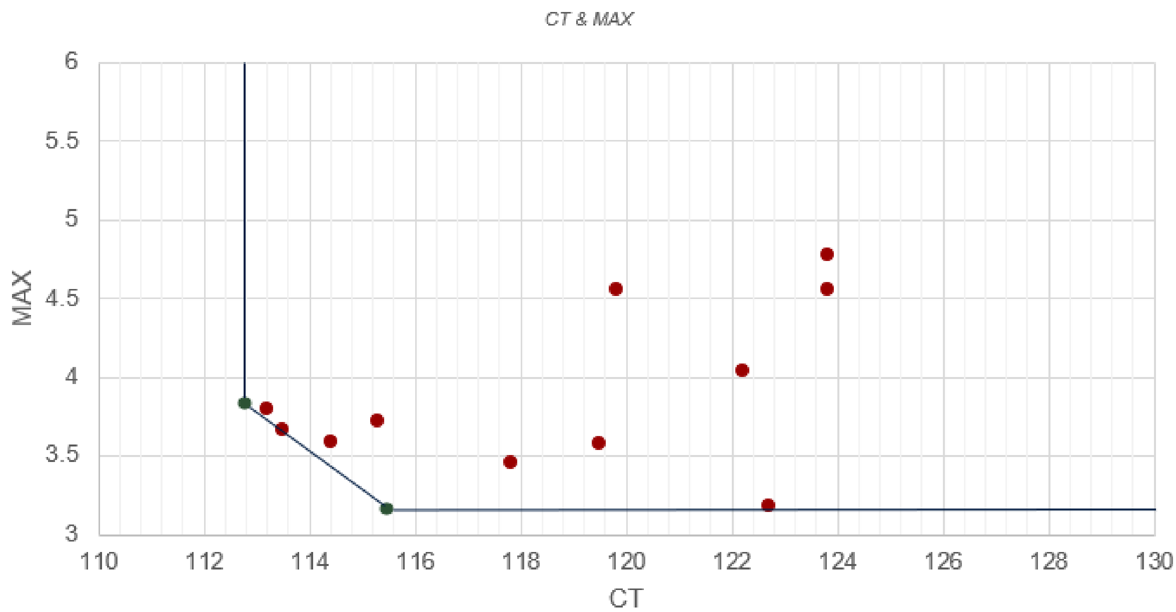

Figure D-5. A2: CT & MAX pareto frontier

B: Including ergonomic data

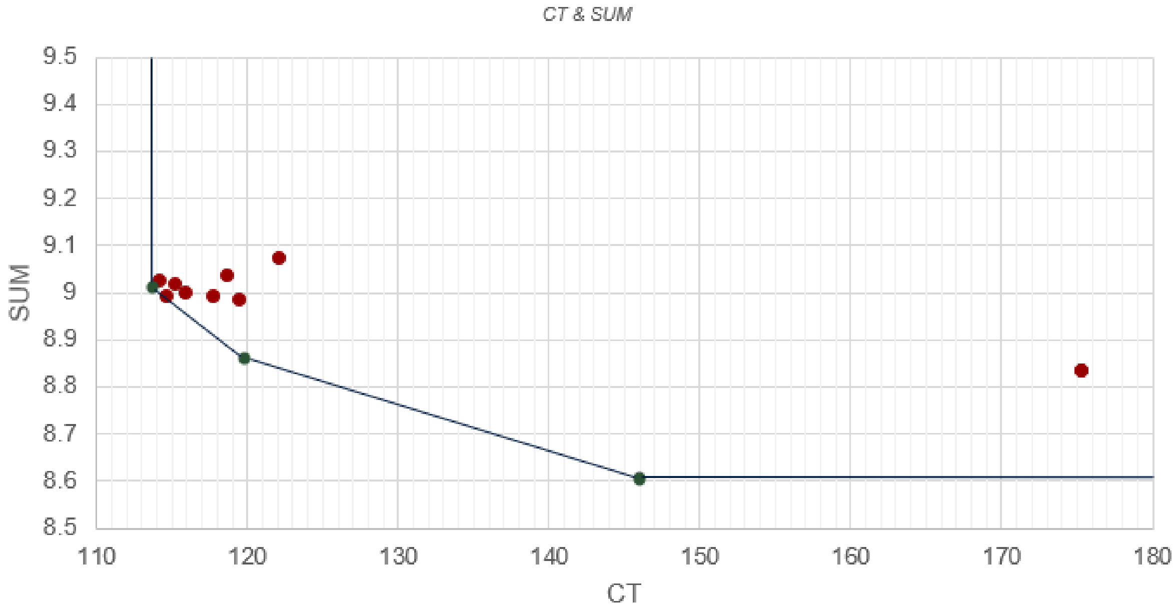

Figure D-6. B: CT & SUM pareto frontier

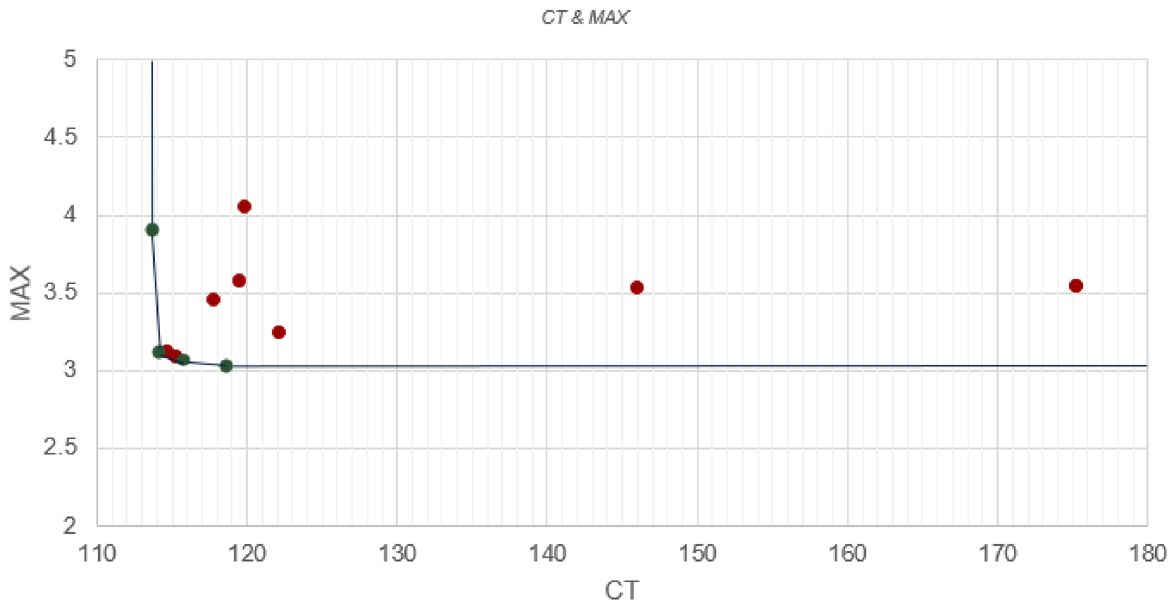

Figure D-7. B: CT & MAX pareto frontier

B: Including ergonomic data – Zoomed in

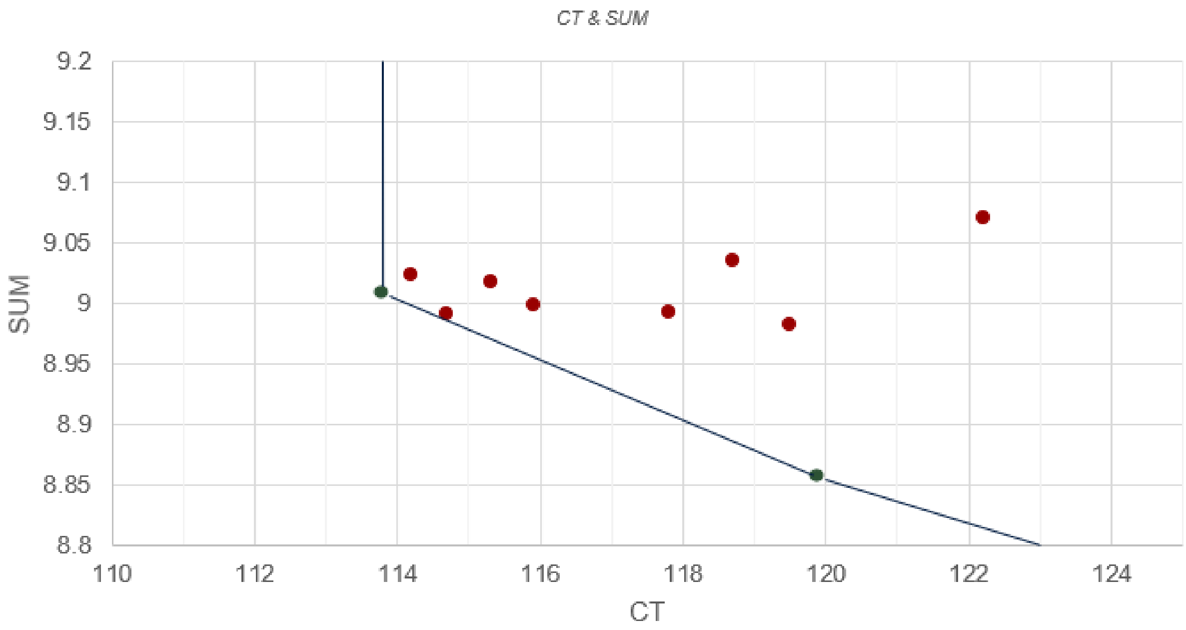

Figure D-8. B: CT & SUM pareto frontier – Zoomed in

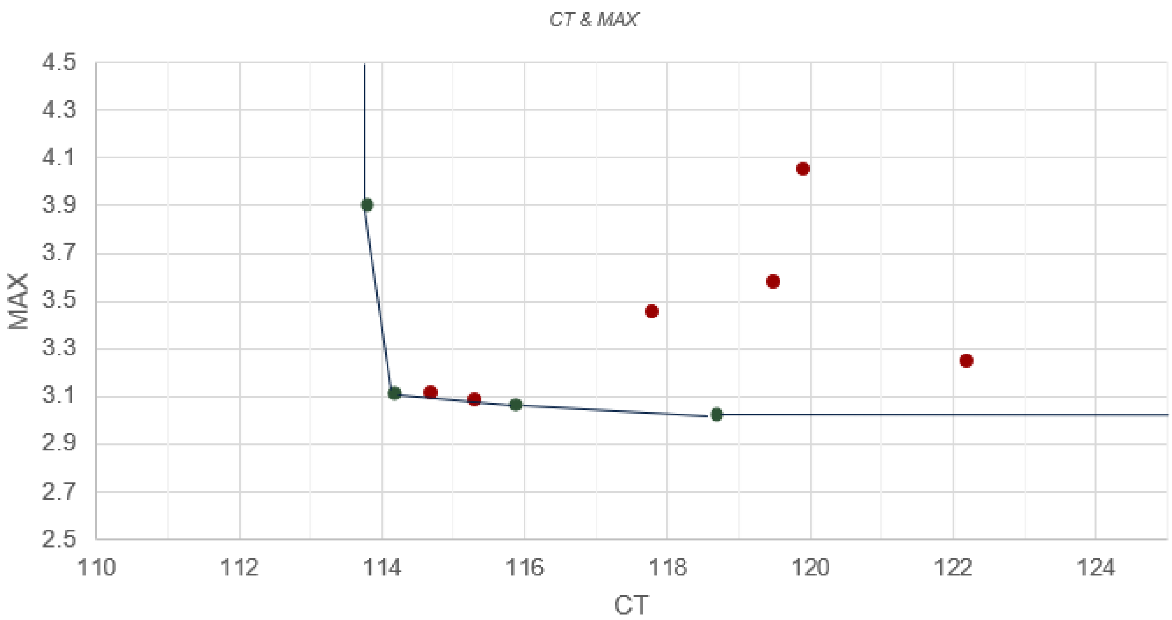

Figure D-9. B: CT & MAX pareto frontier – Zoomed in

Appendix E. Output of statistical analysis manual approach

For the statistical analyses in Section 5.2.2, we used the data as provided in Appendix D.1. and the SPSS software (version 27). Figure E-1 below shows the Ranks of the output and Figure E-2 shows the statistical significance.

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
CTA2 - CTA1	Negative Ranks	5[a]	6.20	31.00
	Positive Ranks	7[b]	6.71	47.00
	Ties	1[c]		
	Total	13		
SUMA2 - SUMA1	Negative Ranks	7[d]	6.50	45.50
	Positive Ranks	6[e]	7.58	45.50
	Ties	0[f]		
	Total	13		
MAXA2 - MAXA1	Negative Ranks	9[g]	7.67	69.00
	Positive Ranks	4[h]	5.50	22.00
	Ties	0[i]		
	Total	13		
CTB - CTA1	Negative Ranks	3[j]	7.00	21.00
	Positive Ranks	10[k]	7.00	70.00
	Ties	0[l]		
	Total	13		
SUMB - SUMA1	Negative Ranks	10[m]	6.70	67.00
	Positive Ranks	2[n]	5.50	11.00
	Ties	1[o]		
	Total	13		
MAXB - MAXA1	Negative Ranks	13[p]	7.00	91.00
	Positive Ranks	0[q]	.00	.00
	Ties	0[r]		
	Total	13		
CTB - CTA2	Negative Ranks	2[s]	4.50	9.00
	Positive Ranks	8[t]	5.75	46.00
	Ties	3[u]		
	Total	13		
SUMB - SUMA2	Negative Ranks	8[v]	6.00	48.00
	Positive Ranks	3[w]	6.00	18.00

	Ties	2[x]		
	Total	13		
MAXB - MAXA2	Negative Ranks	10[y]	6.20	62.00
	Positive Ranks	1[z]	4.00	4.00
	Ties	2[aa]		
	Total	13		

a. CTA2 < CTA1

b. CTA2 > CTA1

c. CTA2 = CTA1

d. SUMA2 < SUMA1

e. SUMA2 > SUMA1

f. SUMA2 = SUMA1

g. MAXA2 < MAXA1

h. MAXA2 > MAXA1

i. MAXA2 = MAXA1

j. CTB < CTA1

k. CTB > CTA1

l. CTB = CTA1

m. SUMB < SUMA1

n. SUMB > SUMA1

o. SUMB = SUMA1

p. MAXB < MAXA1

q. MAXB > MAXA1

r. MAXB = MAXA1

s. CTB < CTA2

t. CTB > CTA2

u. CTB = CTA2

v. SUMB < SUMA2

w. SUMB > SUMA2

x. SUMB = SUMA2

y. MAXB < MAXA2

z. MAXB > MAXA2

aa. MAXB = MAXA2

Figure E-1. Ranks output SPSS

Test Statistics[a]

	CTA2 - CTA1	SUMA2 - SUMA1	MAXA2 - MAXA1	CTB - CTA1	SUMB - SUMA1	MAXB - MAXA1	CTB - CTA2	SUMB - SUMA2	MAXB - MAXA2
Z	-.628[b]	.000[c]	-1.642[d]	-1.712[b]	-2.197[d]	-3.180[d]	-1.887[b]	-1.334[d]	-2.578[d]
Asymp. Sig. (2-tailed)	.530	1.000	.101	.087	.028	.001	.059	.182	.010
Exact Sig. (2-tailed)	.569	1.000	.110	.094	.027	.000	.063	.197	.007
Exact Sig. (1-tailed)	.285	.507	.055	.047	.013	.000	.031	.099	.003
Point Probability	.025	.013	.008	.007	.003	.000	.007	.007	.001

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

c. The sum of negative ranks equals the sum of positive ranks.

d. Based on positive ranks.

Figure E-2. Statistical significance SPSS

Appendix F. MIP single objective runs

The MIP was run for scenario 1, 2 and 3 using different objectives than the one shown in Section 4.3.1. However logical, for completeness we show the different objectives here.

Scenario 1: CT only

$$Min\ OF = CT$$

Scenario 2: SUM only

$$Min\ OF = \sum_j SE_j$$

Scenario 3: MAX only

$$Min\ OF = SE_{max}$$

Appendix G. MIP Results task distribution

This appendix contains the task distribution for all scenarios, as referred to in Section 5.3.1. The tables have the following headers: Task (T), Zone (Z), Station 1, 2 and 3 (S1, S2, S3). The row contains a value 1 in the column of the station it is assigned to.

Scenario 1: CT

Table G-1 shows the MIP task distribution of Scenario 1.

Table G-1. MIP Task distribution Scen1

T	Z	S1	S2	S3		T	Z	S1	S2	S3		T	Z	S1	S2	S3
1	1	1				28	10	1				63	21	1		
2	2	1				29	10	1				64	21	1		
3	2	1				34	11		1			65	21	1		
4	3	1				35	11		1			66	21	1		
5	3	1				36	12		1			67	22			1
6	3	1				37	12		1			68	22			1
7	3	1				38	13		1			69	22			1
8	4	1				39	13		1			70	22			1
9	4	1				40	14			1		71	23			1
10	4	1				41	14			1		72	23			1
11	5			1		42	14			1		73	23			1
12	5			1		43	15			1		74	23			1
13	5			1		44	15			1		75	24			1
14	6	1				45	15			1		76	24			1
15	6	1				46	16			1		77	24			1
16	7	1				47	16			1		78	24			1
17	7	1				48	17			1		79	25	1		
18	7	1				49	17			1		80	26	1		
19	7	1				50	18			1		81	27		1	
20	8	1				51	18			1		82	27		1	
21	8	1				52	18			1		83	28		1	
22	8	1				53	19			1		84	28		1	
23	9		1			54	19			1		85	29		1	
24	9		1			55	19			1		86	29		1	
25	9		1			56	20			1		87	29		1	
26	9		1			57	20			1						
27	10	1				58	20			1						

Scenario 2: SUM

Table G-2 shows the MIP task distribution of Scenario 2.

Table G-2. MIP Task distribution Scen2

T	Z	S1	S2	S3		T	Z	S1	S2	S3		T	Z	S1	S2	S3
1	1	1				28	10		1			63	21		1	
2	2		1			29	10		1			64	21		1	
3	2		1			34	11		1			65	21		1	

4	3		1		35	11		1		66	21		1	
5	3		1		36	12		1		67	22			1
6	3		1		37	12		1		68	22			1
7	3		1		38	13		1		69	22			1
8	4		1		39	13		1		70	22			1
9	4		1		40	14			1	71	23		1	
10	4		1		41	14			1	72	23		1	
11	5			1	42	14			1	73	23		1	
12	5			1	43	15			1	74	23		1	
13	5			1	44	15			1	75	24			1
14	6		1		45	15			1	76	24			1
15	6		1		46	16		1		77	24			1
16	7		1		47	16		1		78	24			1
17	7		1		48	17			1	79	25		1	
18	7		1		49	17			1	80	26		1	
19	7		1		50	18			1	81	27			1
20	8		1		51	18			1	82	27			1
21	8		1		52	18			1	83	28			1
22	8		1		53	19			1	84	28			1
23	9		1		54	19			1	85	29			1
24	9		1		55	19			1	86	29			1
25	9		1		56	20			1	87	29			1
26	9		1		57	20			1					
27	10		1		58	20			1					

Scenario 3: MAX

Table G-3 shows the MIP task distribution of Scenario 3.

Table G-3. MIP Task distribution Scen3

T	Z	S1	S2	S3	T	Z	S1	S2	S3	T	Z	S1	S2	S3
1	1	1			28	10		1		63	21		1	
2	2		1		29	10		1		64	21		1	
3	2		1		34	11		1		65	21		1	
4	3		1		35	11		1		66	21		1	
5	3		1		36	12			1	67	22			1
6	3		1		37	12			1	68	22			1
7	3		1		38	13			1	69	22			1
8	4		1		39	13			1	70	22			1
9	4		1		40	14			1	71	23			1
10	4		1		41	14			1	72	23			1
11	5		1		42	14			1	73	23			1
12	5		1		43	15			1	74	23			1
13	5		1		44	15			1	75	24			1
14	6		1		45	15			1	76	24			1
15	6		1		46	16		1		77	24			1
16	7		1		47	16		1		78	24			1
17	7		1		48	17			1	79	25			1

18	7		1		49	17			1	80	26			1
19	7		1		50	18			1	81	27			1
20	8		1		51	18			1	82	27			1
21	8		1		52	18			1	83	28			1
22	8		1		53	19		1		84	28			1
23	9		1		54	19		1		85	29			1
24	9		1		55	19		1		86	29			1
25	9		1		56	20			1	87	29			1
26	9		1		57	20			1					
27	10		1		58	20			1					

Scenario 4: CT & SUM

Table G-4 shows the MIP task distribution of Scenario 4.

Table G-4. MIP Task distribution Scen4

T	Z	S1	S2	S3	T	Z	S1	S2	S3	T	Z	S1	S2	S3
1	1	1			28	10	1			63	21		1	
2	2	1			29	10	1			64	21		1	
3	2	1			34	11	1			65	21		1	
4	3	1			35	11	1			66	21		1	
5	3	1			36	12			1	67	22			1
6	3	1			37	12			1	68	22			1
7	3	1			38	13			1	69	22			1
8	4		1		39	13			1	70	22			1
9	4		1		40	14			1	71	23		1	
10	4		1		41	14			1	72	23		1	
11	5			1	42	14			1	73	23		1	
12	5			1	43	15			1	74	23		1	
13	5			1	44	15			1	75	24			1
14	6	1			45	15			1	76	24			1
15	6	1			46	16		1		77	24			1
16	7	1			47	16		1		78	24			1
17	7	1			48	17	1			79	25		1	
18	7	1			49	17	1			80	26		1	
19	7	1			50	18	1			81	27		1	
20	8		1		51	18	1			82	27		1	
21	8		1		52	18	1			83	28		1	
22	8		1		53	19		1		84	28		1	
23	9	1			54	19		1		85	29		1	
24	9	1			55	19		1		86	29		1	
25	9	1			56	20		1		87	29		1	
26	9	1			57	20		1						
27	10	1			58	20		1						

Scenario 5: CT & MAX

Table G-5 shows the MIP task distribution of Scenario 5.

Table G-5. MIP Task distribution Scen5

T	Z	S1	S2	S3		T	Z	S1	S2	S3		T	Z	S1	S2	S3
1	1	1				28	10	1				63	21		1	
2	2	1				29	10	1				64	21		1	
3	2	1				34	11	1				65	21		1	
4	3	1				35	11	1				66	21		1	
5	3	1				36	12		1			67	22			1
6	3	1				37	12		1			68	22			1
7	3	1				38	13			1		69	22			1
8	4		1			39	13			1		70	22			1
9	4		1			40	14			1		71	23		1	
10	4		1			41	14			1		72	23		1	
11	5		1			42	14			1		73	23		1	
12	5		1			43	15			1		74	23		1	
13	5		1			44	15			1		75	24			1
14	6	1				45	15			1		76	24			1
15	6	1				46	16		1			77	24			1
16	7	1				47	16		1			78	24			1
17	7	1				48	17		1			79	25	1		
18	7	1				49	17		1			80	26	1		
19	7	1				50	18		1			81	27	1		
20	8		1			51	18		1			82	27	1		
21	8		1			52	18		1			83	28			1
22	8		1			53	19		1			84	28			1
23	9	1				54	19		1			85	29			1
24	9	1				55	19		1			86	29			1
25	9	1				56	20			1		87	29			1
26	9	1				57	20			1						
27	10	1				58	20			1						

Appendix H. Zones dataset

This appendix contains the dataset of tasks grouped by zones, shown in Table H-1. We refer to this appendix in Section 5.3.2. The times (both red and black)are composed of the sum of all task times of tasks belonging to that zone. The Time-Weighted Average REBA is calculated over all tasks and task times belonging to that zone. The precedence graph belonging to this dataset is shown in the main text, Section 4.2, as Figure 4-13.

Table H-1. Grouped zones dataset

Zone	Time black	Time red	TWAR black	TWAR red
1	0.00	0.00	0.00	0.00
2	8.98	11.08	4.00	4.00
3	11.90	11.90	3.42	3.42
4	8.10	0.00	2.82	0.00
5	15.20	15.20	2.93	2.93
6	15.60	15.60	4.17	4.17
7	21.50	21.50	1.90	1.90
8	11.50	11.50	2.77	2.77
9	13.60	13.60	2.63	2.63
10	12.00	12.00	2.93	2.93
11	12.20	0.00	6.16	0.00
12	27.30	0.00	6.90	0.00
13	27.10	27.10	2.57	2.57
14	11.20	11.20	5.02	5.02
15	10.90	8.90	3.20	2.80
16	3.40	3.40	1.00	1.00
17	7.20	7.20	1.00	1.00
18	9.80	9.80	1.00	1.00
19	8.20	8.20	1.00	1.00
20	15.40	15.40	4.17	4.17
21	10.60	10.60	1.79	1.79
22	8.80	8.80	1.27	1.27
23	10.40	10.40	1.46	1.46
24	11.50	11.50	1.11	1.11
25	3.80	3.80	1.00	1.00
26	7.40	7.40	1.00	1.00
27	4.50	4.50	1.00	1.00
28	6.40	6.40	2.50	2.50
29	20.90	20.90	2.24	2.24

Appendix I. Genetic algorithm results

In this appendix we show the results of all GA scenarios' 10 runs, as referred to in Section 5.3.2. All run result tables contain the following unencountered abbreviations in their headers: ITBS Iteration of Best Solution, CPUBS = CPU time of Best Solution, CPUT = CPU time total, OFV = Objective Function Value

Scenario 1: CT

Table I-1 shows the run results of Scenario 1. Table I-2 shows the task distributions of the runs of Scenario 1.

Table I-1. Run results Scenario 1

run	CT	SUM	MAX	ITBS	CPUBS	CPUT	OFV
1	112.90	9.00047	3.763574	127	20.6905	197.5294	0.010227
2	112.70	9.04488	4.11159	128	25.34679	202.1826	0.008379
3	113.28	9.03694	3.25627	1519	254.4893	407.7364	0.013740
4	112.78	8.98269	4.241047	212	33.24413	189.5254	0.009119
5	113.08	9.02450	4.206803	99	15.25993	170.3062	0.011891
6	112.50	9.01608	3.260882	660	111.9774	279.2441	0.006530
7	113.50	8.99049	3.8739	63	10.00216	170.6961	0.015772
8	111.90	9.00265	3.376338	306	53.28235	227.6405	0.000985
9	112.60	8.98728	3.911185	83	12.28758	168.8149	0.007455
10	113.50	9.00737	3.375571	811	141.2706	319.655	0.015772

Table I-2. Task distribution of runs Scenario 1

run	Task Dist													
1	S1	1	21	25	26	27	2	3	5	4	6	10	11	
	S2	12	13	14	15	7	8	16						
	S3	19	9	17	18	23	28	29	20	22	24			
2	S1	1	2	23	3	4	5	6	7	9	17			
	S2	18	21	10	13	11	12	14						
	S3	15	25	26	27	28	29	8	16	19	20	22	24	
3	S1	1	2	25	21	3	4	6	10	13	5			
	S2	7	9	17	18	14	15	11	23	8	16			
	S3	19	20	22	24	12	26	27	28	29				
4	S1	1	2	25	23	3	6	10	11	12	21			
	S2	13	26	27	28	29	5	14	15	4				
	S3	7	8	16	19	9	17	18	20	22	24			
5	S1	1	21	25	26	23	2	3	6	7	9	17		
	S2	18	27	28	29	4	8	5	16	19	20	22		
	S3	24	10	11	13	14	12	15						
6	S1	1	2	3	5	4	6	7	25	26	27	9		
	S2	17	21	18	10	13	14	15	11	8				
	S3	16	19	20	22	24	28	29	23	12				
7	S1	1	21	23	25	26	2	27	28	29	3	4	6	
	S2	7	9	17	18	10	13	14	15					
	S3	11	12	8	16	19	20	24	22	5				
8	S1	1	23	25	26	2	3	4	27	28	21	6	10	11
	S2	12	13	7	9	17	8	16						
	S3	19	18	29	14	15	20	22	24	5				

9	S1	1	23	21	25	26	27	28	2	3	4	6	10	11
	S2	13	14	15	12	5	29							
	S3	7	9	17	18	8	16	19	20	22	24			
10	S1	1	23	21	2	25	26	27	3	6	5	10	4	
	S2	13	11	7	9	17	14	15	18					
	S3	28	29	8	16	19	20	24	22	12				

Scenario 2: SUM

Table I-3 shows the run results of Scenario 2. Table I-4 shows the task distributions of the runs of Scenario 2.

Table I-3. Run results Scenario 2

run	CT	SUM	MAX	ITBS	CPUBS	CPUT	OFV
1	331.58	5.023472	3.023472	77	19.74848	272.6479	0.048178
2	331.58	5.023472	3.023472	103	29.39479	304.0563	0.048178
3	331.58	5.023472	3.023472	74	25.70271	306.8172	0.048178
4	331.58	5.023472	3.023472	38	10.30618	314.5043	0.048178
5	331.58	5.023472	3.023472	103	30.40519	305.3101	0.048178
6	331.58	5.023472	3.023472	21	5.086091	308.1228	0.048178
7	331.58	5.023472	3.023472	13	3.985376	283.5911	0.048178
8	331.58	5.023472	3.023472	84	22.98274	325.8862	0.048178
9	331.58	5.023472	3.023472	133	42.82574	379.7065	0.048178
10	331.58	5.023472	3.023472	3	0.694624	268.1092	0.048178

Table I-4. Task distribution of runs Scenario 2

run	Task Dist																											
1	S1	1																										
	S2	25																										
	S3	26	2	3	6	7	9	17	10	11	12	8	16	19	18	20	22	4	27	28	29	5	21	23	13	14	15	24
2	S1	1																										
	S2	25																										
	S3	2	23	26	27	21	28	29	3	4	5	6	10	11	7	9	17	18	8	16	19	20	24	12	22	13	14	15
3	S1	1																										
	S2	25																										
	S3	26	27	21	28	2	3	4	6	5	10	13	14	15	23	7	9	17	8	16	19	29	11	12	18	20	24	22
4	S1	1																										
	S2	25																										
	S3	2	21	26	23	3	5	6	7	9	17	18	27	28	29	4	8	16	19	20	22	24	10	13	11	12	14	15
5	S1	1																										
	S2	2																										
	S3	23	26	27	28	29	2	3	4	6	7	9	8	16	17	19	5	18	20	24	22	21	10	11	12	13	14	15
6	S1	1																										
	S2	25																										
	S3	23	26	2	3	5	6	7	9	10	17	18	8	11	12	13	14	15	16	19	20	22	24	21	27	28	29	4
7	S1	1																										
	S2	25																										
	S3	2	21	23	3	6	5	7	9	17	18	4	10	11	12	26	27	28	29	13	14	15	8	16	19	20	24	22

8	S1	1																										
	S2	25																										
	S3	23	2	3	4	5	21	26	27	28	6	7	8	16	19	10	11	12	13	14	15	9	17	18	20	22	24	29
9	S1	1																										
	S2	25																										
	S3	21	2	3	4	26	5	6	7	9	17	8	16	19	23	27	28	29	10	11	13	12	14	15	18	20	24	22
10	S1	1																										
	S2	25																										
	S3	21	2	3	4	23	26	5	6	7	8	16	19	10	11	12	9	17	18	20	22	24	13	14	15	27	28	29

Scenario 3: MAX

Table I-5 shows the run results of Scenario 3. Table I-6 shows the task distributions of the runs of Scenario 3.

Table I-5. Run results Scenario 3

run	CT	SUM	MAX	ITBS	CPUBS	CPUT	OFV
1	171.4	7.0010091	3.0023	159	38.229	268.2032229	0.143022962
2	320.18	6.9377039	3.0037	48	12.178	267.4966172	0.143121704
3	171.08	7.0010898	3.0006	495	128.2	383.9987775	0.142896661
4	320.18	6.9377039	3.0037	317	78.425	324.1902023	0.143121704
5	171.08	7.0010898	3.0006	962	223.61	457.0066052	0.142896661
6	171.08	7.0010898	3.0006	18	4.1604	267.8214765	0.142896661
7	320.18	6.9377039	3.0037	38	8.9913	250.7093683	0.143121704
8	196.18	7.001117	3.0006	779	206.58	475.4532035	0.142902812
9	171.08	7.0010898	3.0006	459	120.99	380.934025	0.142896661
10	320.18	6.9377039	3.0037	681	175.87	511.7975897	0.143121704

Table I-6. Task distribution of runs Scenario 3

run	Task Dist																											
1	S1	1																										
	S2	2	3	5	4	21	6	7	9	17	10	11	13															
	S3	25	26	27	28	29	14	15	8	16	19	18	20	22	24	23	12											
2	S1	1																										
	S2	21	25	26	2	23	27	28	29	3	4	6	10	7	8	11	12	16	19	9	13	14	15	17	18	20	24	22
	S3	5																										
3	S1	1																										
	S2	2	25	26	27	28	29	23	21	3	6	4	10	11	13	14												
	S3	12	15	5	7	8	16	19	9	17	18	20	22	24														
4	S1	1																										

	S2	21	2	23	3	6	10	13	14	7	8	16	19	15	11	12	25	9	17	18	20	24	22	4	26	27	28	29
	S3	5																										
5	S1	1																										
	S2	21	25	26	2	23	27	28	29	3	4	6	10	13	11	14												
	S3	15	5	7	9	17	18	12	8	16	19	20	22	24														
6	S1	1																										
	S2	21	23	25	26	27	28	29	2	3	6	10	11	4	13	14												
	S3	15	5	7	9	17	8	16	19	18	20	22	24	12														
7	S1	1																										
	S2	23	2	25	26	27	3	6	4	7	9	10	13	14	11	12	15	17	8	16	19	28	29	21	18	20	22	24
	S3	5																										
8	S1	1																										
	S2	23	21	2	3	6	10	11	7	9	17	8	16	13	14	15	4											
	S3	5	12	18	19	20	22	24	25	26	27	28	29															
9	S1	1																										
	S2	2	23	21	25	26	27	28	29	3	6	4	10	13	14	11												
	S3	12	15	5	7	8	9	17	18	16	19	20	24	22														
10	S1	1																										
	S2	25	26	27	28	29	2	3	4	23	6	10	11	12	7	8	16	19	21	9	17	18	20	24	22	13	14	15
	S3	5																										

Scenario 4: CT & SUM

Table I-7 shows the run results of Scenario 4. Table I-8 shows the task distributions of the runs of Scenario 4.

Table I-7. Run results Scenario 4

run	CT	SUM	MAX	ITBS	CPUBS	CPUT	OFV
1	112.5	9.007371	3.524016	23	6.344016	273.0174	0.074782
2	112.4	9.005947	3.46454	89	24.51656	321.2566	0.074302
3	112.5	9.005751	3.355566	154	40.37133	298.4267	0.074762
4	112.4801	9.041952	4.244378	227	67.38033	352.275	0.075101
5	112.2	9.013745	3.778457	646	179.6823	469.9573	0.073471
6	112.5801	8.991792	3.767555	361	101.2859	389.0928	0.074966
7	112.6801	9.005746	4.376126	120	32.30054	249.4667	0.075594
8	112.5801	8.99611	3.224038	879	216.3127	490.5458	0.075018

9	112.4801	9.035785	3.879576	233	58.67103	296.2128	0.075028
10	112.5801	9.003462	3.147281	712	174.8365	421.2407	0.075105

Table I-8. Task distribution of runs Scenario 4

run	Task Dist												
1	S1	1	21	23	2	3	6	10	11	4	7		
	S2	9	8	16	19	5	12	17	18	20			
	S3	24	22	13	14	15	25	26	27	28	29		
2	S1	1	23	21	2	3	4	6	7	10	11		
	S2	12	9	17	5	18	13	8					
	S3	16	19	20	22	24	14	15	25	26	27	28	29
3	S1	1	25	23	2	3	6	10	7	8	16	11	
	S2	12	5	19	4	26	27	28	29	9			
	S3	17	21	18	20	22	24	13	14	15			
4	S1	1	23	2	3	4	5	6	7	9	17		
	S2	18	10	11	12	13	14	15					
	S3	8	16	19	20	24	22	21	25	26	27	28	29
5	S1	1	2	21	23	25	3	4	6	7	9	17	
	S2	18	10	11	12	8	16	19	13				
	S3	14	15	26	27	28	29	20	24	22	5		
6	S1	1	23	25	21	2	3	6	10	11	13		
	S2	5	12	14	15	4	26	27	28	29			
	S3	7	8	16	19	9	17	18	20	24	22		
7	S1	1	2	3	5	6	7	21	9	4	17		
	S2	10	11	13	14	15	12	8					
	S3	25	26	27	23	18	16	19	20	22	24	28	29
8	S1	1	21	23	25	2	3	6	10	13	11		
	S2	7	14	15	9	5	4	8	16	19	17		
	S3	18	20	22	24	26	27	28	29	12			
9	S1	1	23	2	3	6	4	5	7	9	17		
	S2	21	10	11	18	12	8	13					
	S3	14	15	25	26	27	28	29	16	19	20	22	24
10	S1	1	21	2	23	3	25	26	27	5	6	10	11
	S2	12	4	7	8	16	9	17	19	18			
	S3	20	24	22	28	29	13	14	15				

Scenario 5: CT & MAX

Table I-9 shows the run results of Scenario 5. Table I-10 shows the task distributions of the runs of Scenario 5.

Table I-9. Run results Scenario 5

run	CT	SUM	MAX	ITBS	CPUBS	CPUT	OFV
1	115.9	9.021105	3.107798	102	27.00145	304.3582	0.094254
2	113.5	9.012992	3.196192	575	146.3463	413.0561	0.086321
3	113.1	9.016889	3.414624	268	79.54888	354.7778	0.092274
4	113.3	9.004429	3.370684	380	94.3958	354.2224	0.091629
5	113.2	9.015767	3.48395	172	39.4937	283.8914	0.095212
6	114.5	9.06146	3.356834	116	31.67584	276.5916	0.096679
7	115.5	8.999872	3.188859	479	109.9234	336.9347	0.095301
8	111.9	9.000307	3.451283	119	30.66798	280.9187	0.088039

9	116.1	9.039256	3.14614	517	124.5381	367.7709	0.096548
10	113.3801	9.02664	3.212778	25	5.93208	259.651	0.08636

Table I-10. Task distribution of runs Scenario 5

run	Task Dist													
1	S1	1	23	2	3	5	4	6	7	10				
	S2	13	14	11	15	8	25	26	27	28	29			
	S3	21	16	19	12	9	17	18	20	22	24			
2	S1	1	21	25	26	27	28	29	2	3	4	6	10	
	S2	13	14	11	15	5	7	9						
	S3	17	18	8	16	19	20	22	24	12	23			
3	S1	1	21	25	2	23	3	5	6	10	7			
	S2	9	17	18	8	11	13	14	4	16	19			
	S3	15	20	22	24	26	27	28	29	12				
4	S1	1	21	25	26	2	3	6	10	11	13			
	S2	5	7	9	8	16	19	17	18	14	15			
	S3	12	20	22	24	4	27	28	29	23				
5	S1	1	21	2	23	25	3	5	6	7	10			
	S2	8	16	19	11	12	9	17	18	4	26	27		
	S3	28	29	20	22	24	13	14	15					
6	S1	1	23	25	2	3	4	6	10	13	14			
	S2	11	7	8	16	9	19	5	21	26	27	28		
	S3	29	15	12	17	18	20	24	22					
7	S1	1	25	2	21	23	3	5	4	6	7			
	S2	9	17	10	13	14	15	8	11	18				
	S3	12	26	27	28	29	16	19	20	22	24			
8	S1	1	25	23	26	27	21	28	2	3	6	10	11	4
	S2	13	12	5	7	9	17							
	S3	8	16	18	19	14	15	20	22	24	29			
9	S1	1	2	3	6	7	8	9	4	5				
	S2	21	25	26	27	28	29	10	11	13	14			
	S3	12	15	23	17	18	16	19	20	24	22			
10	S1	1	21	25	26	27	28	29	2	3	4	5	6	
	S2	7	8	16	10	13	14	11	9					
	S3	17	18	12	19	20	22	24	15	23				

Appendix J. IPS-IMMA simulation time consumption

Table J-1 shows the time consumed to create the IPS-IMMA simulations of tasks, as we refer to in Section 6.2.

Table J-1. IMMA simulations' time consumption

Task Nr	Description	Zone	IPS Sim	Time spent (minutes)
0	START	1	-	
2	Pick up front frame	2	1	30
3	Mount front frame	2	1	10
4	Go to material storage - steering column	3	-	
5	Remove packaging from steering column	3	1	30
6	Go to pedal car	3	-	
7	Mount steering column	3	1	30
8	Fetch clippers	4	-	
9	Cut cable tie	4	1	15
10	Put away tool	4	-	
11	Fetch screw and washer-rear of steering column	5	-	
12	Mount rear screw of steering column	5	1	30
13	Tighten rear screw	5	1	
14	Fetch screw and washer-front of steering column	6	-	
15	Mount front screw of steering column	6	1	20
16	Fetch nuts and washers, 2pc	7	-	
17	Mount nut and washer right steering link	7	1	15
18	Go to other side of pedal car	7	-	
19	Mount nut and washer left steering link	7	1	
20	Grasp powertool	8	1	10
21	Tighten left steering link screw	8	1	10
22	Put away tool	8	1	10
23	Grasp powertool	9	1	
24	Go to other side of pedal car	9	-	
25	Tighten right steering link screw	9	1	5
26	Put away wrench and powertool	9	1	
27	Fetch torque wrench	10	-	
28	Change angle of steering column, tighten front screw of steering column	10	1	20
29	Put away tool	10	-	
34	Fetch screw, nut and washer	11	-	
35	Enter screw in cap	11	1	60
36	Fetch tool	12	-	
37	tighten screw in cap	12	1	20
38	fetch steering wheel screw and washer	13	-	
39	mount steering wheel	13	1	30
40	fetch tool	14	-	
41	tighten steering wheel	14	1	15

42	Put away tool	14	-	
43	take rubber mallet	15	-	
44	mount emblem	15	1	45
45	put away rubber mallet	15	-	
46	Fetch front left wheel	16	1	15
47	Place front left wheel	16	1	30
48	Fetch front right wheel	17	1	15
49	Place front right wheel	17	1	30
50	Fetch screw and washer 1pc	18	-	
51	Go to pedal car	18	-	
52	Enter screw front right	18	1	15
53	Fetch screw and washer 1pc	19	-	
54	Go to pedal car	19	-	
55	Enter screw front left	19	1	5
56	Tighten front left wheel	20	1	15
57	Go to front right wheel	20	-	
58	Tighten front right wheel	20	1	10
63	fetch a wheelhub cap	21	-	
64	Go to rear left wheel	21	-	
65	Mount a wheelhub cap	21	1	15
66	Bring back hammer	21	-	
67	fetch a wheelhub cap	22	-	
68	Go to front left wheel	22	-	
69	Mount a wheelhub cap	22	1	10
70	Bring back hammer	22	-	
71	fetch a wheelhub cap	23	-	
72	Go to rear right wheel	23	-	
73	Mount a wheelhub cap	23	1	10
74	Bring back hammer	23	-	
75	fetch a wheelhub cap	24	-	
76	Go to front right wheel	24	-	
77	Mount a wheelhub cap	24	1	10
78	Bring back hammer	24	-	
79	Read Mona	25	-	
80	Mount washer on bracket	26	1	10
81	Go to pedal car	27	1	15
82	Place chair bracket	27	1	10
83	Fetch chair	28	1	45
84	Place chair on bracket	28	1	10
85	Fetch screw and torque wrench	29	-	
86	Enter screw and tighten chair	29	1	15
87	Put away tool	29	-	
		TOTAL	40 tasks	690 minutes
			TIME SPENT	11.5 hours