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## FAULT-TOLERANT FLOW-LINE DESIGN: AN EXAMPLE FROM AN AUTOMOTIVE BODY SHOP

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FAULT-TOLERANT FLOW-LINE DESIGN  
AN EXAMPLE FROM AN AUTOMOTIVE BODY SHOP  
BY  
CHRISTOPH MÜLLER

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF  
THE REQUIREMENTS FOR THE DEGREE OF  
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UNIVERSITY OF RHODE ISLAND

2013

MASTER OF SCIENCE THESIS  
OF  
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## Abstract

Automotive companies employing highly automated assembly lines in their body shops struggle with the challenge of robots' failures which result either in stoppages of the line or in manual backup of operations. These phenomena tend to impair the systems' productivity as well as the products' quality. Therefore, the consideration of robot failures in the design stage of an assembly line considerably gains in importance. In this thesis we develop an approach to configure a robotic assembly line such that it is more robust against robots' failures. The principle idea is that in the event of a robot failure, working robots perform the tasks of failed robots. The throughput loss in these backup situations mainly depends on the systems' level of redundancy, i.e. the higher the systems' level of redundancy the more robust it is against robot failures. Consequently, we develop an approach to design the line such that the systems' level of redundancy is maximized.

We provide a numerical analysis in which we compare the performance of our approach with that of a traditional robotic assembly line balancing robot. In order to evaluate our approach we use performance measures for the average cycle time and the product quality. In all settings considered we find that our approach performs better as the benchmark with regard to both evaluation criteria. The best performance with regard to the cycle time is obtained for a low to medium number of welding guns per group of weld spots and a relatively low mean time between failure *MTBF*. Our approach allows for a reduction of the cycle time of 2 % to 4 % compared to the benchmark. When considering the product quality we get the best performance for a medium to high number of welding guns per group of spots for both values of the *MTBF* that have been considered. The number of groups of

spots that have to be backed up manually could be reduced by approximately 60%. From this we derive that our approach is best suited for a manufacturing environment which is characterized by frequent but short robot failures and a medium number of welding guns per group of spots.

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## List of Acronyms

<b>ALB</b>	assembly line balancing
<b>BIW</b>	body in white
<b>CAD</b>	computer aided design
<b>CNC</b>	computer numerical control
<b>DCWs</b>	dimensional control welds
<b>DNC</b>	direct numerical control
<b>FA</b>	final assembly
<b>FTRALBP</b>	fault-tolerant robotic assembly line balancing problem
<b>GM</b>	General Motors
<b>GRB</b>	general robot backup formulation
<b>IFR</b>	International Federation of Robotics
<b>ISO</b>	International Standardization Organization
<b>MTBF</b>	mean time between failure
<b>MTTR</b>	mean time to repair
<b>NVH</b>	noise, vibration and harshness characteristics
<b>OEMs</b>	original equipment manufacturers
<b>RALBP</b>	robotic assembly line balancing problem
<b>RCM</b>	robot capability matrix

<b>RDF</b>	redundancy factor
<b>RSPs</b>	respot welds
<b>RSW</b>	resistance spot welding
<b>SCARA</b>	Selective Compliance Assembly Robot Arm
<b>VDP</b>	vehicle development process
<b>WCM</b>	welding gun capability matrix

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## Chapter 1

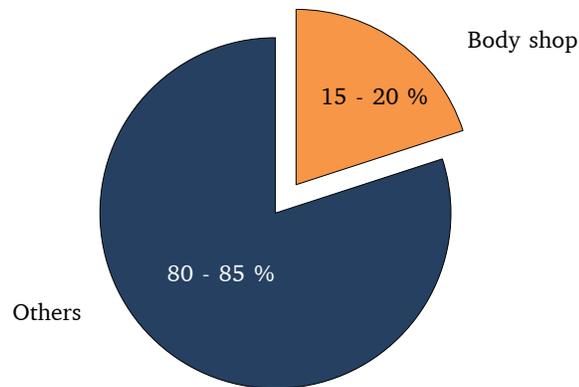
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### Introduction

#### 1.1 Current situation and problem statement

Today's manufacturing environment is characterized by a high degree of global competition, high cost pressure, high product diversification, as well as shorter innovation and product life-cycles. For cost efficient mass production of standardized products, assembly lines have been developed and implemented in many different industries such as the automotive and household appliance industries. Assembly lines are flow oriented production systems where the different workstations performing repetitive sets of tasks on the products are aligned in a serial manner. The products visit the stations of the system successively as they are moved along the line which is usually done by some kind of transportation system (e.g., a conveyor belt or automated guided vehicles). Due to the high investment as well as running costs, the problem of configuring assembly lines, i.e. the assignment of tasks to workstations with regard to some objective, is of great interest for both practitioners as well as researchers.

During the past decades, automation technology has been deployed extensively for assembly lines, thereby changing the requirements for decision support systems for the configuration of such systems. Highly automated assembly lines are usually implemented wherever the work environment is in some form hostile to workers or whenever industrial robots are able to perform tasks with higher precision than human workers (Boysen, Fliedner, and Scholl, 2008). Advantages of increasing



**Figure 1.1:** Structure of the production costs of an automobile. (Wemhöner, 2006, 25)

automation are for instance, increased productivity, greater efficiency and better scrap prevention. On the other hand, new challenges arise due to high automation such as more complex control systems, very high investments for equipment, as well as machine breakdowns. Breakdowns of machinery become an especially relevant issue not only in short-term planning and control but also when configuring automated assembly lines, because the breakdown of a single machine or tool can result in the stoppage of the whole line (Boysen, Fliedner, and Scholl, 2008).

One industry which has been traditionally highly automated is the automotive industry. Especially the body and paint shops of automotive plants are characterized by a high degree of automation. The automation level in the body shop of a typical advanced automotive plant has reached 95 % or more. Typically, 3,500 to 4,000 spot welds (Naitoh et al., 1997) are performed by up to one hundred or even more welding robots leading to investments for the equipment, which sometimes exceed one hundred million dollars (Spieckermann et al., 2000). The high investments are directly reflected in the structure of the production costs of an automobile, which is illustrated in figure 1.1. It can be seen that the costs caused by the body shop account for 15 - 20 % of the total production costs. Hence, high productivity of the body shop has to be ensured. However, assembly lines in automotive body shops are usually characterized by robots' failures, which result either in line stoppages

or manual backup of tasks both leading to decreased productivity while the latter also tends to impair products' quality. Therefore, breakdowns of robots should be considered in the design stage of these systems in order to ensure minimum productivity loss in the event of failures.

So far, only a few studies on assembly line balancing directly address the problem of breakdowns of machinery despite increasing automation of assembly lines. Previous research in this field has concentrated on the assignment of buffers between the workstations of the assembly line to cope with unreliable machines. However, buffers do have several disadvantages: while the investments for the installation of buffers are relatively small, buffers are characterized by high operation as well as maintenance costs. Furthermore, buffers require much space on the shop floor and increase the overall lead time of the assembly system. (Spieckermann et al., 2000) Therefore, small buffer sizes are desired.

Another approach to make highly automated body assembly lines robust against robots' failures is to configure the line such that downstream robots can perform the operations of failed upstream robots during repair times. The ability of a downstream robot to perform the operations of a failed robot mainly depends on its tool configuration as well as its physical location in the line. As the number of robots that are capable of performing other operations than those originally assigned to them increases, the systems' level of redundancy increases, too. As a consequence, the assembly line is more robust against robots' failures. Hence, the following question arises: how should the robots in the line be equipped with different tools such that both the productivity and the robots' redundancy in the system are maximized?

## 1.2 Objectives and approach

Against this background the overall goal of this thesis is to develop a mathematical model for robust flow-line design, which seeks to determine a line configuration which ensures minimal productivity loss as well as high product quality during repair times of failed robots.

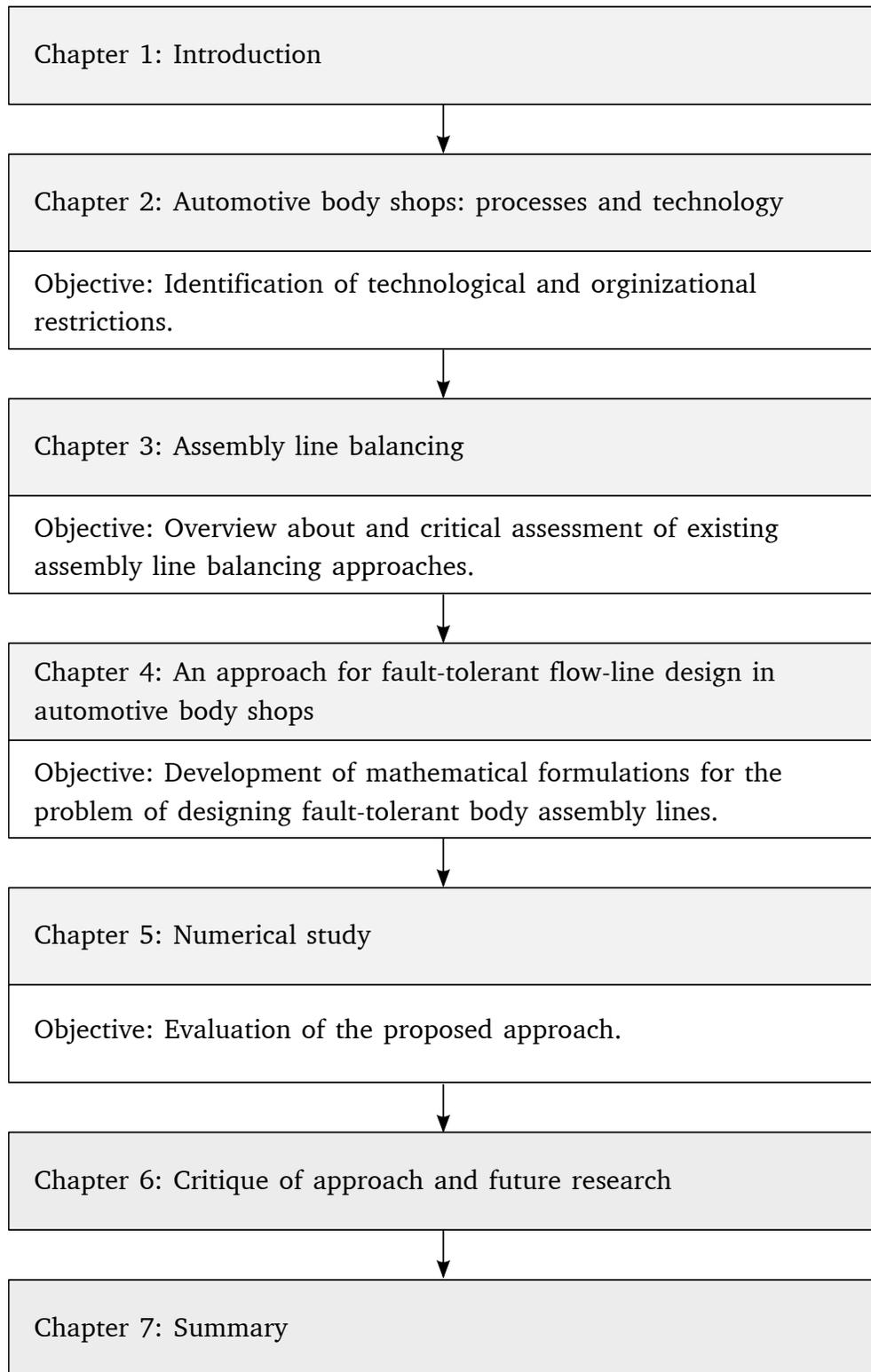
The thesis has been divided into six additional chapters. First, chapter 2 gives an introduction to body-shop systems in the automotive industry. Therefore, we start with a discussion of the processes of an automotive body shop. After briefly describing all stages of an automotive plant, the body assembly process is discussed in detail. Then we move on to consider the equipment which is used in the different assembly operations, which are required to assemble the body shell of an automobile. Based on these information about automotive body shop systems we can later derive technological restrictions, which have to be considered in our approach for fault-tolerant design of body assembly lines.

Chapter 3 then moves on to provide a detailed analysis of the existing approaches in the assembly line balancing literature. After introducing the basic terms related to assembly line production, simple and generalized assembly line balancing problems and the solution procedures for those problems are presented. The discussion of generalized assembly line balancing problems focuses on extensions for automated assembly lines as well as lines producing large products such as automobiles. The existing approaches are then evaluated with regard to their suitability for the purpose of fault-tolerant flow-line design.

Since none of the existing approaches considers robots' failures at the design stage of assembly lines, chapter 4 presents an approach for fault-tolerant design of automotive body assembly lines.

In chapter 5 a numerical study is carried out in order to evaluate the proposed approach. The objectives of the numerical study are twofold. Above all, we want to investigate the performance of our approach as compared to a benchmark that does not take into account robots' failures at the design stage of the line. Furthermore, we want to identify operating conditions for which the approach is particularly well suited. The results of our study are presented and discussed in detail. In order to evaluate our approach we use performance measures for the average cycle time and the product quality.

Chapter 6 provides a critical assessment of the developed approach and offers some recommendations for future research. Finally, chapter 7 gives a summary of the thesis. The outline of the thesis is illustrated in Figure 1.2.



**Figure 1.2:** Structure of the thesis.

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## Chapter 2

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### **Automotive body shops: processes and technology**

This section gives an introduction to body-shop systems in the automotive industry. This stage of automotive production is traditionally highly automated and therefore robots' failures become a relevant planning issue in the long-term configuration of body assembly lines.

This chapter is organized as follows. In section 2.1 we will describe the processes of automotive body shops. First, the different stages of an automotive plant will be introduced and then we move on to discuss the body assembly process in detail. In section 2.2 we will provide a detailed description of the equipment which is used in the body assembly process - mainly industrial robots equipped with different types of welding guns - in order to identify technological restrictions that have to be considered for an approach of fault-tolerant flow-line design for automotive body shops.

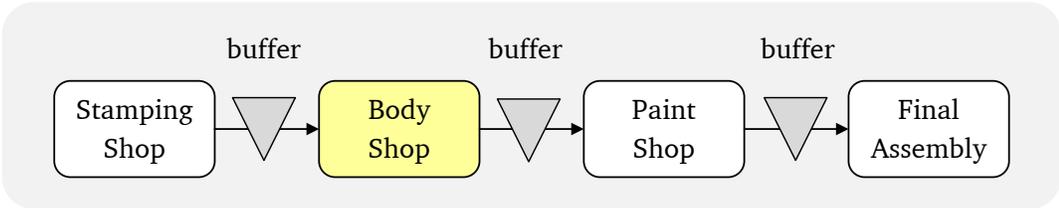
#### **2.1 Processes of an automotive body shop**

The automotive body shop is the stage in an automotive plant in which sheet metal panels are assembled together. Typically, the activities carried out in an automotive body shop cover fixturing, welding, and transportation between the different workstations of the assembly line. This section gives an overview about the processes of an automotive body shop. First, all stages of an automotive plant will be briefly discussed in order to clarify the dependencies between the different shops

in the plant. Then, we will describe the processes of the body assembly line in detail.

### 2.1.1 Stages of an automotive plant

In the automotive industry, the typical structure of a plant for car manufacturing involves four main production stages: stamping shop, body shop, paint shop and final assembly (FA) (Michalos et al., 2010). The shops are each decoupled by buffers of limited size. A simplified illustration of the material flow through the different shops is shown in figure 2.1. The different stages of an automotive plant differ with regard to the equipment which is used as well as the automation level. In the following we will describe the four stages of automobile production.



**Figure 2.1:** Stages of an automotive plant. (Askar and Zimmermann, 2007)

The assembly sequence of an automobile starts in the stamping shop where coils, which are typically made out of steel or aluminum, are delivered. The metal sheets or blanks are then transferred to the stamping press lines where the different parts for the vehicle are formed. A typical vehicle body skeleton, usually referred to as body in white (BIW), consists of three to four hundred stamped sheet metal pieces. (Omar, 2011, Chapter 1.2.1) After the stamping process the finished parts are transferred to a storage area from where they are fed to the body shop or body weld area.

In the body shop area, the stamped parts are assembled to panels (e.g., side panel,

floor assembly) in several sub-assembly lines before the BIW is assembled in the main line. This stage of the automotive plant is usually highly automated. (Naitoh et al., 1997; Omar, 2011, Chapter 1.2.1) A more detailed discussion of the body assembly process, which is the focus of this thesis, is provided in section 2.1.3.

The completed BIW is then transferred to the paint shop. In the paint shop the surface of the BIW is first prepared and then lacquered. This stage of the automotive plant is generally fully automated. If the coated car bodies meet the criteria for paint quality they are transferred to a storage area which decouples the paint shop and the final assembly area. (Askar and Zimmermann, 2007; Omar, 2011, Chapter 1.2.1)

In the last stage of an automotive plant, the final assembly, the interior and exterior (e.g., cockpit, seats) trims are installed. This stage of an automotive plant is characterized by a high degree of manual labor due to the fact that this stage requires a high degree of flexibility in order to assemble the large number of different variants. (Askar and Zimmermann, 2007; Omar, 2011, Chapter 1.2.1)

### **2.1.2 Structure of the body in white**

The performance of a BIW is mainly dependent on the following criteria: crash-worthiness (also referred to as passive safety), service life (or durability), as well as its noise, vibration and harshness characteristics (NVH). Furthermore, new metrics such as the structure recyclability and weight efficiency considerably gained in importance over the past years mainly to enhance the energy efficiency of vehicles. These criteria, which define the overall performance of the vehicle's structure, are determined by the choice of material, its shape selections and the manufacturing processes. (Omar, 2011, 1)

The BIW consists of three main sub-assemblies: floor assembly, body side panels

(left and right) and the roof. These sub-assemblies which are illustrated in figure 2.2 are made out of several hundred blanks in the sub-assembly lines and then fed into the main line where the BIW is assembled.

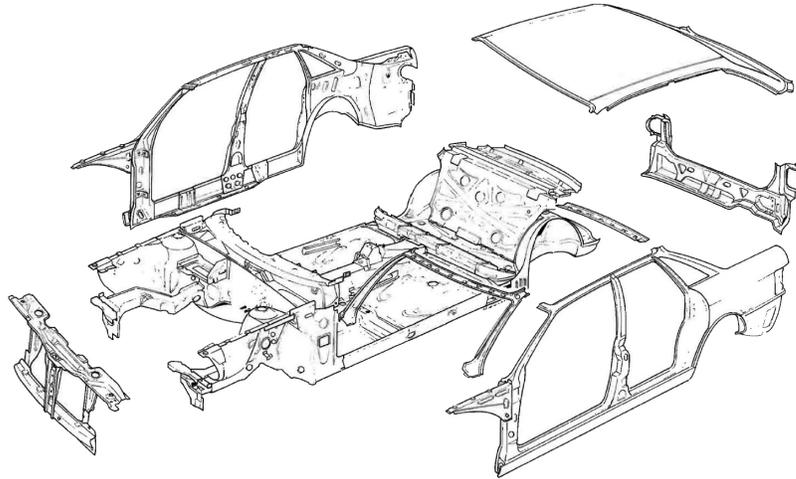
The large floor assembly, also referred to as underbody or platform, is composed of the front end, rear floor and front floor. It forms the floor of a vehicle and the position of its external and structural panels. It is the most important part of modern vehicles, because most cars obtain their rigidity mainly from the platform chassis. The body side panels mainly consist of the three pillars (A, B, and C) as well as the inner and outer panels of the roof frame. The roof of an automobile sits above the passenger compartment and is composed of the roof skin, which is stabilized by the roof frame and the roof bows. Finally, attachment parts such as the doors, the trunk and the hood are assembled to the body shell. (Omar, 2011, 1-4)

The BIW is mainly made from steel and aluminum sheets of different grades. The motivation for the choice of steel and aluminum is mainly due to their advantageous performance with regard to their dent resistance, energy absorption, strength and stiffness. Furthermore, these materials have favorable manufacturing characteristics, i.e. they provide good formability, weldability and paintability at comparatively low cost. (Omar, 2011, 41)

### **2.1.3 The body assembly process**

This section focuses on the activities involved in the body shop area of an automotive plant. These activities cover fixturing, welding, and transportation between the different workstations as well as related support activities.

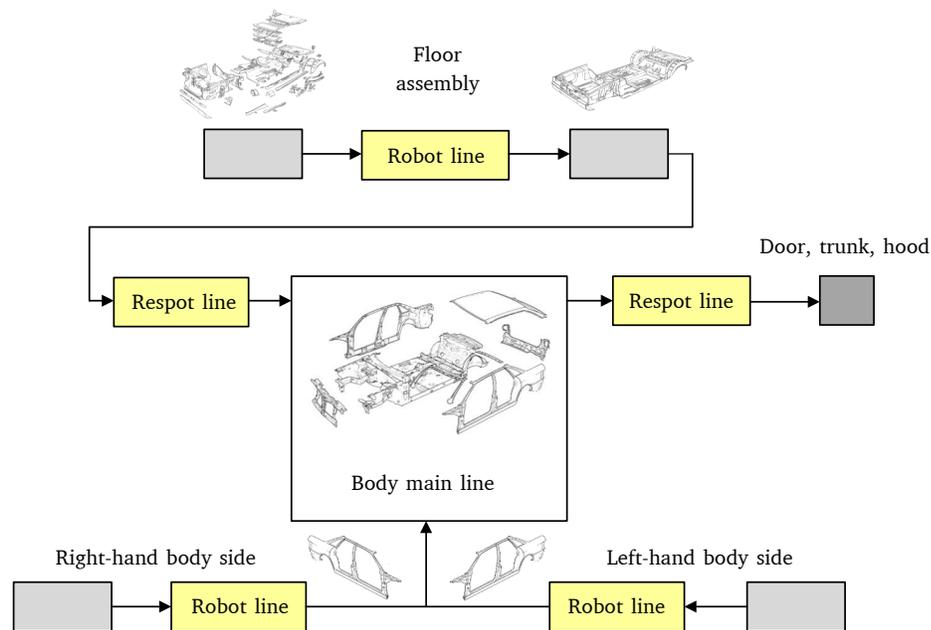
The automotive body shop consists of a main assembly line and several sub-assembly lines. Several hundred pressed blanks are transferred from the in-house stamping



**Figure 2.2:** Typical body shell construction. (Pippert, 1998)

shop and vendor facilities to the sub-assembly lines of the body shop where the panels (e.g., B-pillar) and the sub-assemblies (e.g., side panel) are joined mainly by resistance spot welding and other joining techniques (e.g., bonding, riveting) in a planned sequence at a number of stations which are connected by a conveyor belt. The sub-assemblies are then fed into the main body line at appropriate locations. A simplified illustration of the typical layout of a body welding shop is given in figure 2.3. The front end, rear floor and front floor are transferred to the underbody line where the floor structure is welded. The floor structure is then brought to the body main line. The right-hand and left-hand body side panels are fed into the main line after all sub-assembly operations are done in separate lines. (Naitoh et al., 1997; Omar, 2011, 134-137)

Each line contains several robotic cells (also called stations), each of which consist of several welding robots that are working simultaneously. The robots are equipped with welding guns and grippers for material handling (Kahan et al., 2009). Two different types of robotic cells, namely, geometry or framing cells and respot cells are distinguished. In the geometry cells new parts are welded to the vehicle's body to define a new geometry of the vehicle. These stations are usually equipped with



**Figure 2.3:** Typical layout of a body welding shop. (Naitoh et al., 1997)

an automated material handling system and sometimes a dedicated robot only for material handling activities. Using jigs and fixtures, the parts which are to be assembled are held in the right position and a few spot welds are applied to maintain the integrity of the shell. After framing, the bodies pass down a respot line. In the respot cells, spot welds are performed on the existing geometry and no new part is assembled. The sole purpose of these stations is to give each vehicle's body its engineering strength and high torsional stiffness. A typical car undergoes 3,500 to 4,000 spot welds (Naitoh et al., 1997). Large cars, such as the Rover 75 undergo 5,400 spot welds, of which 3,000 spots are respot welds (RSPs) (Rooks, 1999). Generally, RSPs account for about 85 % of the total number of spots (Kahan et al., 2009).

As can be seen from the description, resistance spot welding (RSW) is the most important joining technique in automotive manufacturing. However, due to new materials used to reduce the weight of automotive bodies, new joining techniques

such as adhesive bonding, laser welding or clinching considerably gain in importance.

Due to increasing product variety, different models of the same product (e.g., sedan, station wagon, coupé) are offered in most production series in the automotive industry. Furthermore, customers can choose from a variety of different options (e.g., with or without sunroof, left-hand drive or right-hand drive) resulting in an increased number of variants on the shop floor. These models are all assembled on the same assembly line leading to fluctuations in the processing times of the different stations. While the floor assembly of the different models is mostly identical, the side panels and the roof require different numbers of spot welds. The stations are configured for the model with the highest number of spot welds. However, these models are usually characterized by the lowest production volume. Hence, the utilization of the stations is not optimal for the other models assembled on the line. To maintain a high utilization in this manufacturing environment, the welding operations of the different models have to be assigned to the stations such that the average workload of the station is balanced. This procedure is called assembly line balancing (ALB) and will be discussed in detail in chapter 3.

## **2.2 Assembly operations and equipment in automotive body shops**

This chapter will discuss the assembly operations in automotive body shops, the equipment which is used for them, as well as some of the activities involved with regard to its automation. We will focus on resistance spot welding performed by industrial robots due to the fact that this is the most important joining technique used in the body assembly process. First, section 2.2.1 will discuss the technology of and the equipment used for resistance spot welding in automotive body shops. Then, section 2.2.2 describes the structure and components of industrial robots

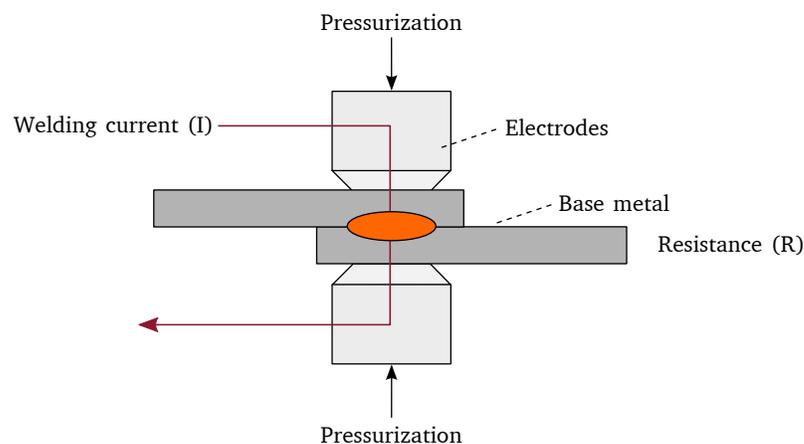
which are heavily used in automotive body shops.

### 2.2.1 Resistance spot welding

Resistance spot welding (or just spot welding) is the dominating joining technique in automotive body shops. This is mainly due to the low operating costs and the high process reliability. Furthermore, the resistance spot welding process is highly suitable for automation. (Dennison, Toncich, and Masood, 1997)

#### Technology

Resistance spot welding is accomplished when a current is caused to flow between the electrode tips and the sheet metal panels to be joined. Due to the resistance of the base metal induced by the welding current, a localized heat described by Ohm's law is caused in the joint. This heating leads to the formation of the weld nugget at the interface between the two sheet metal panels. (Omar, 2011, 118) The resistance welding process is illustrated in figure 2.4. As can be seen, the two metal sheet panels to be joined are inserted between two welding electrodes.



**Figure 2.4:** The details of the spot welding process. (Omar, 2011, 121)

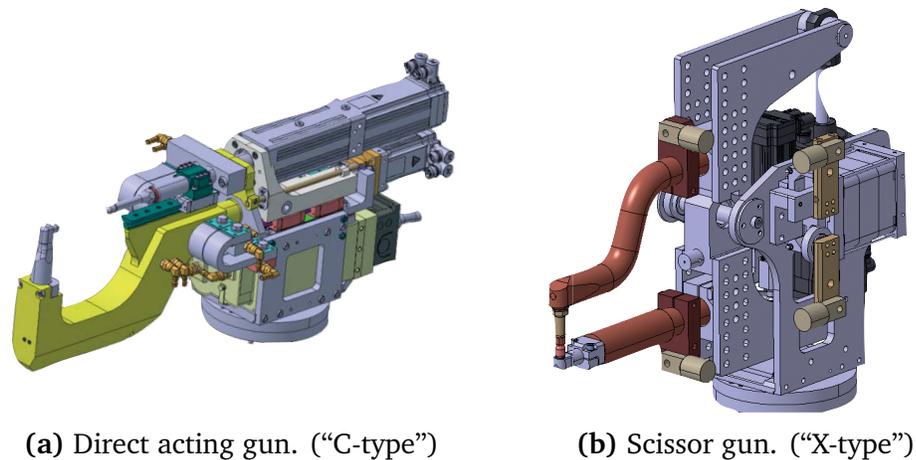
The spot welding process can be separated into different phases or times: the first phase is the squeeze time, which is the time when the mechanical pressure is applied to the sheet metal panels. During this period no welding current is applied.

The second phase is the heat or weld time when the welding current is flowing from the upper electrode through the sheet metal panels to the lower electrode. The third phase is referred to as hold time, which is the time when the mechanical pressure is maintained after the weld current is turned off. Finally, the electrodes are separated in the fourth phase. At this stage the weld join is permanent. (Omar, 2011, 121)

## **Equipment**

The spot welding tool (referred to as a spot welding gun) is the key mechanical and electrical element of any spot welding system. In the following we will describe the characteristics of welding guns. We will focus on the design of welding guns, because an important requirement of any spot-welding process carried out by robots is to ensure that the weld locations can be reached by the welding gun. This discussion does not cover the electrical system, which is necessary to generate the high welding currents between 6 and 10 kA (for mild steel) although it is included in the welding gun.

Spot welding guns are composed of a transformer, a secondary circuit, a cooling system and a pressure element. Two different types of spot welding guns can be distinguished: direct acting guns and scissor guns. Direct acting guns are characterized by a linear electrode movement while the arms of the electrodes of a scissor gun are connected by a hinge leading to a light circular electrode movement. Two computer aided design (CAD) drawings of a direct acting gun - also referred to as "C-type" gun - and a scissor gun - also referred to as "X-type" gun - are illustrated in figures 2.5a and 2.5b, respectively. While the different types of welding guns have no impact on the fundamental operation of a welding gun, they are very important for access to weld locations (Dennison, Toncich, and Masood, 1997). In addition to the welding gun type, other design parameters such as length, diameter and



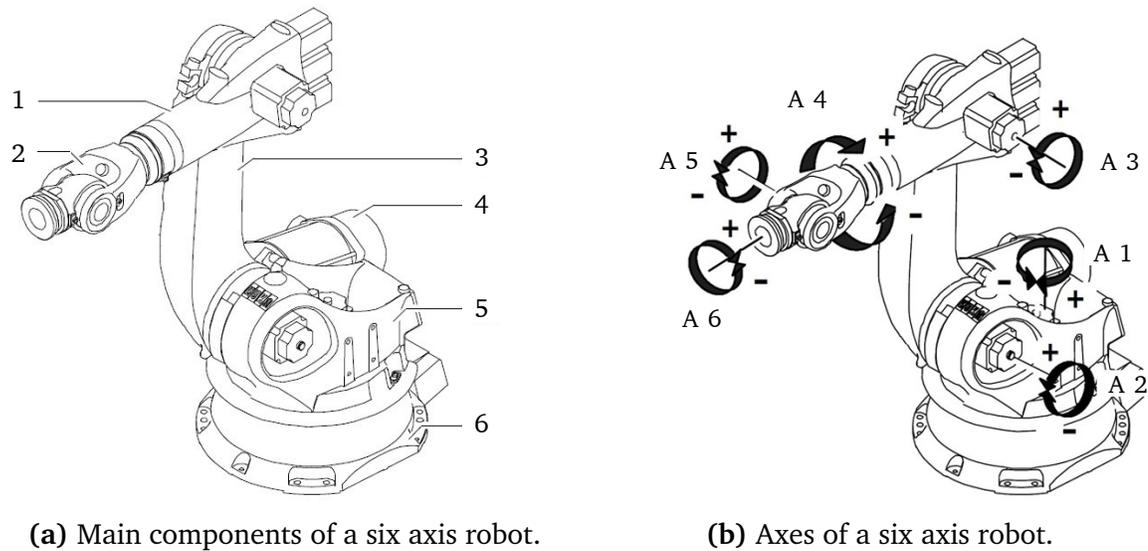
**Figure 2.5:** Automotive spot welding guns. (Dalex, 2013)

angle of the welding tool determine whether a certain welding gun can reach a weld location. During the planning stage of an automotive vehicle development process (VDP), welding guns have to be selected and assigned to individual manufacturing operations. This is usually done by analyzing the CAD data of the body shell in order to generate feasible assembly sequences, create the manufacturing operations and assign the tools. In a typical automotive plant, it is common to find a high number of different welding gun variants. (Gupta et al., 2012) For instance, in the automotive body shops of the German car manufacturer Daimler up to 350 different welding gun variants have been used (Tschauner, 2005).

### 2.2.2 Industrial robots

The International Standardization Organization (ISO) defines an industrial robot as an “automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes” in the ISO 8334 standard. The main difference between an industrial robot and a computer numerical control (CNC) machine is the versatility of the robot, which can be equipped with different tools and has a relatively large work envelope compared to its size.

In 1969 General Motors (GM) installed the first 26 spot-welding robots at its Lord-



**Figure 2.6:** Design of a six axis KUKA robot. (IT-Material, 2013)

stown assembly plant in Ohio. These robots, installed by Unimation, boosted productivity and allowed more than 90 percent of all body welding operations to be automated. In traditional plants only 20 to 40 % of welding operations were carried out automatically at this time. Then in 1970 Daimler-Benz in Germany also used Unimate robots for body-side spot welding. (Nof, 1999, 867) The automotive industry with its high output, high investment levels and also intense competition in global markets has had an extensive effect on the development and operation of industrial robots ever since and enabled the extensive use of industrial robots (Muller, 1982). Nowadays, all major car manufacturers use industrial robots for spot welding operations due to their speed, accuracy and repeatability (Nof, 1999, 867). The automotive industry is the most important purchaser of industrial robots and accounted for 36 % of the total annual supply of industrial robots in 2011 (International Federation of Robotics (IFR), 2012).

### Structure and components of industrial robots

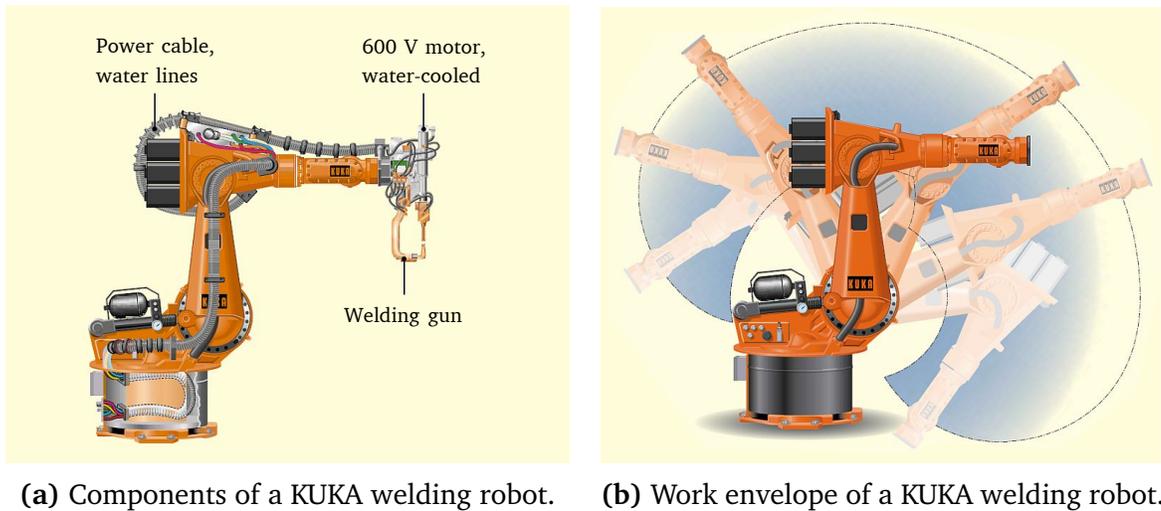
In addition to the mechanical structure, an industrial robot consists of different

subsystems: power supply, motion control, sensors and manipulator. The mechanical structure is composed of the main components, which are illustrated in figure 2.6a, namely, end effector (1), upper arm (2), lower arm (3), counterbalance (4), rotary head (5) and base (6). The arms connected by joints form the kinematic chain. The configuration of the kinematic chain determines the size and shape of the work envelope and determines the capability of the robot to move the end effector to a certain position and orientation. Most industrial robots have open-chain structures, however, other kinematic solutions based on closed kinematic chains exist (parallel robots) but are not used for welding operations in automotive plants.

Industrial robots have various axis configurations. Each configuration has certain advantages and disadvantages and the selection of robots always depends on the case of application. The vast majority of articulated robots, however, feature six axes, also called six degrees of freedom, because six axis robots allow for greater flexibility and can perform a wider variety of applications than robots with fewer axes such as a Selective Compliance Assembly Robot Arm (SCARA). Six axis robots have three main axes (A1, A2 and A3 in figure 2.6b), which define the work envelope. The the upper arm and the wrist axes (A4, A5 and A6 in figure 2.6b) are used for the orientation of the end-effector.

### **Requirements for welding robots**

Industrial spot welding robots have to meet a number of requirements, namely, spatial accessibility, high accuracy, high payload capacity and high acceleration and velocity. Spot welding requires a large number of degrees of freedom. Therefore, welding robots have six axes, which enables them to reach almost every weld location depending on the welding gun with which they are equipped. An illustration of the work envelope of a KUKA welding robot is shown in figure 2.7b.



**Figure 2.7:** KUKA welding robot. (IT-Material, 2013)

To maintain high product quality, industrial robots have to achieve high accuracy in terms of deviation in weld positions and gun alignment. Welding robots' deviations only range between 0.5 - 1.0 mm. In comparison, manual spot welding can reach up to +/- 20mm in deviation from the specified weld location. Nevertheless, virtually all welding lines in the automotive industry still have manual repair stations which can backup operations while robots are offline. (Omar, 2011, 140-142)

Since current spot welding robots integrate all the welding equipment, tooling and accessories in one unit they need a high payload capacity, because weld guns with an integrated transformer weigh approximately 150 kg. Figure 2.7a illustrates a KUKA welding robot equipped with a C-type welding gun, the transformer which is integrated into the robot as well as water lines and power supply. Due to the high number of spot welds for each car body, welding robots have to maintain high velocity and acceleration despite the heavy weld guns in order to ensure low cycle times. (Omar, 2011, 140-142)

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## Chapter 3

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### Assembly line balancing

Assembly lines are flow-oriented production systems where stations performing repetitive tasks are aligned in a serial manner. Due to the high investment as well as high running costs of these production systems, the problem of configuring assembly lines is of great importance for both researchers and practitioners. Hence, this problem has gained a lot of attention in the scientific community over the past decades and a large amount of different optimization models, which aim at supporting the decision maker in the configuration of such systems, has been developed. Since the assembly line balancing problem is of great importance for the industry, the development of efficient solution procedures, which can provide good solutions within reasonable time has also attracted widespread attention. Therefore, a great number of different solution procedures has been published as well.

This chapter is organized as follows. After introducing the basic terms related to assembly line production, section 3.1 provides an overview of the different optimization models, which can be distinguished in the literature on assembly line balancing. Section 3.2 then moves on to discuss solution methods for different assembly line balancing problems. This contains the presentation of both exact and approximate solution procedures for assembly line balancing problems. Finally, section 3.3 provides a critical assessment of the existing assembly line balancing models for automated lines with regard to the consideration of machines which are unreliable.

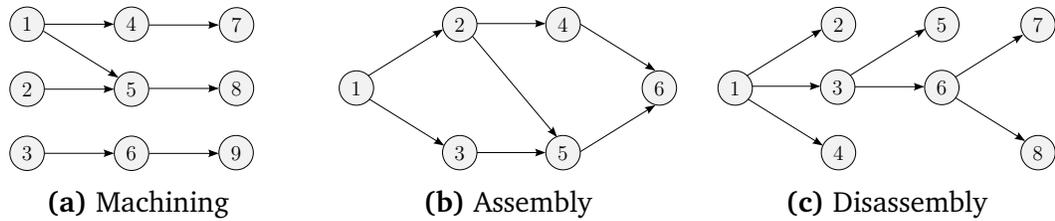
### 3.1 Assembly line balancing problems

The problem of configuring assembly lines has been labeled as *assembly line balancing* (ALB) and is of great interest for both researchers as well as practitioners. The first mathematical formulation of this problem has been presented by [Salveson \(1955\)](#). A great body of literature on assembly line balancing problems has evolved ever since. Due to the very different conditions in industrial manufacturing, a great variety of optimization models for the configuration of assembly lines can be distinguished. After introducing the basic terms related to assembly line balancing in section 3.1.1 the different assembly line balancing problems will be discussed. First, section 3.1.2 provides an overview about the different versions of the simple assembly line balancing problem. Then, section 3.1.3 discusses generalized assembly line balancing problems, which consider many more aspects of real-world balancing problems.

#### 3.1.1 Basic terms of assembly line production

Before discussing the different optimization models for the configuration of assembly lines, this section defines the basic terms related to assembly line production. Some of these terms have already been used intuitively before. In the following, we will provide precise definitions.

An *operation* is a portion of the total work content in an assembly, which is indivisible, which means it cannot be split into smaller work elements without creating unnecessary additional work. For instance, an operation in a manual assembly process may consist of the following steps: (1) reaching for a screw driver, (2) grasping it, (3) taking the screw and putting it into the thread, (4) tightening the screw, and finally (5) returning the tool. ([Scholl, 1999](#), 4)



**Figure 3.1:** Precedence graphs. (Battaia and Dolgui, 2013)

A (*work*)station is a segment of the assembly line where a number of different operations is performed. Workstations are mainly characterized by the machinery and equipment as well as the operations assigned to them. Depending on the degree of automation, manual, semi-automated, and automated workstations can be distinguished. Traditionally, assembly lines were characterized by a high degree of manual labor. However, during the past decade automation technology has been deployed extensively for assembly lines. Fully automated lines are referred to as transfer lines, which are equipped with fully automated machines (CNC or DNC machines) performing the different operations. (Scholl, 1999, 4) These lines are usually implemented, if the work environment is in form hostile to human beings, as for instance in the body and paint shops of the automobile industry, or wherever industrial robots are able to perform tasks more economically or with a higher precision (Boysen, Fliedner, and Scholl, 2008).

For most products *precedence constraints* between the operations have to be observed due to technological or organizational restrictions. These elements are usually summarized and visualized by means of precedence graphs. These graphs contain nodes for each operation, node weights for the processing times of each operation, as well as arcs for the direct and paths for the indirect precedence relations. (Scholl, 1999, 5) Figure 3.1 shows possible precedence graphs for machining, assembly, and disassembly lines, respectively. The node weights are not illustrated in this figure for reasons of clarity.

The *cycle time* is defined as the maximum amount of time a workpiece can be processed by a station to meet customer demand. Usually the cycle time is smaller than the longest processing time of all operations. A possible difference between the cycle time and the station time is called idle time, since the station is idle after performing the assigned work content. (Scholl, 1999, 5)

The term line balancing has already been used intuitively in previous sections without providing a precise definition. A *line balance* is defined as a feasible task assignment. In this context a feasible solution is characterized mainly by the following properties: Each task is assigned to exactly one station. The precedence relations are considered, which means that no operation  $i$  which must succeed an operation  $h$  is assigned to an earlier station than  $i$ . The sum of the processing times of the operations assigned to one station does not exceed the cycle time. (Scholl, 1999, 5) However, as generalized assembly line balancing problems become more complex to consider real-world settings, a feasible solution may be characterized by more properties than those listed above (e.g., assignment of operations to stations requires the station to be equipped with the right tools).

### **3.1.2 The simple assembly line balancing problem**

Since the first mathematical formulation of the assembly line balancing problem by Salveson (1955), a substantial amount of research has been devoted to the core problem of the configuration of assembly lines, which is the assignment of tasks to stations. This stream of research has been labeled as *simple assembly line balancing problem* (SALBP) in the widely accepted review of Baybars (1986) since this problem is based on numerous simplifying assumptions. The assembly line balancing problem is assigning tasks to workstations with respect to a certain objective, i.e. either minimizing the number of stations for a given cycle time (SALBP-1), or minimizing the cycle time for a given number of stations (SALBP-2), or maximizing

**Table 3.1:** Versions of SALBP. (Becker and Scholl, 2006)

	Cycle Time $c$	
	Given	Minimize
No. $m$ of stations		
Given	SALBP-F	SALBP-2
Minimize	SALBP-1	SALBP-E

the line efficiency (SALBP-E) while satisfying precedence constraints of the products. Furthermore, the problem of finding a feasible balance for a given number of stations is known as SALBP-F. Table 3.1 illustrates the different versions of the SALBP, which will be discussed in the following.

All four versions of the SALBP are based on the same set of limiting assumptions (Baybars, 1986; Boysen, Flidner, and Scholl, 2007; Becker and Scholl, 2006):

- (S-1) Mass-production of one homogeneous product.
- (S-2) All operations are processed in a predetermined mode (no processing alternatives exist).
- (S-3) Paced line with a fixed common cycle time according to a desired output quantity.
- (S-4) The line is considered to be serial with no feeder lines or parallel elements.
- (S-5) The processing sequence of operations is subject to precedence restrictions.
- (S-6) Deterministic (and integral) processing times  $t_i$ .
- (S-7) No assignment restrictions of tasks besides precedence constraints.
- (S-8) An operation cannot be split among two or more stations.
- (S-9) All stations are equally equipped with respect to machines and workers.

In the following, we start our presentation with the objective-independent feasibility problem (SALBP-F), which only seeks for a feasible line balance without consideration of any objective. Then we will move on to discuss the objectives mentioned above, namely the minimization of the line length (SALBP-1), the minimization of the cycle time (SALBP-2). Finally, the problem of optimizing both objectives simultaneously, i.e. maximizing the line efficiency (SALBP-E) is described.

### The feasibility problem (SALBP-F)

In the absence of an objective function, the *feasibility problem* SALBP-F consists of determining whether or not a line balance exists for a given number of  $m$  stations and a given cycle time  $c$ . A feasible solution of a problem instance has to satisfy the constraints (3.1) - (3.4). Let  $x_{ij}$  be a binary decision variable which takes the value 1 if operation  $i$  is assigned to station  $j$ . The cycle time as well as the number of stations are given with  $c$  and  $m$ , respectively. Furthermore, the immediate predecessors of operation  $i$  are given by the set  $P(i)$ . With this notation, we can state SALBP-F as follows:

$$\sum_{k=1}^m x_{ij} = 1 \quad \forall j \in J \quad (3.1)$$

$$x_{ik} \leq \sum_{j=1}^k x_{hj} \quad \forall i \in I, \quad k \in J, \quad h \in P(i) \quad (3.2)$$

$$\sum_{j=1}^n x_{ij} \cdot t_i \leq c \quad \forall i \in I \quad (3.3)$$

$$x_{ij} \in \{0, 1\} \quad \forall i \in I, \quad j \in J \quad (3.4)$$

Constraint (3.1) ensures that each operation  $i$  is assigned to exactly one station  $j$ . Equation (3.2) controls the precedence relationships between the operations while constraint (3.3) ensures that the sum of processing times of all operations assigned to a station does not exceed the cycle time. As stated before, the decision variable is binary, which is expressed in equation (3.4). If the model has a feasible solution for given cycle time  $c$  and number of stations  $m$ , the respective SALBP-F instance has a positive answer. Otherwise, no line balance exists for the given values.

### **Minimizing the number of stations (SALBP-1)**

The most famous version of the SALBP is the one which seeks to minimize the number of stations in the line (SALBP-1). Hence, SALBP-1 can be interpreted as an extension of SALBP-F, which arises due to the introduction of the number  $m$  of stations as another decision variable and supplementing the objective of minimizing  $m$  (cf. Scholl, 1999, 42). In the following we will describe how the formulation (3.1) - (3.4) of the SALBP-F has to be modified in order to formulate SALBP-1. First, the former parameter  $m$  has to be introduced as a decision variable. Second, the SALBP-F formulation has to be augmented by an objective function, which expresses the goal of minimizing the number of stations. Since the number of stations  $m$  is introduced as a decision variable in the SALBP-1 formulation, an upper bound on the number of stations  $\bar{m}$  is required. Upper bounds are useful in reducing the number of constraints and variables in the optimization model. Different upper bounds can be found in the literature. For instance, the most simple upper bound equals the number of tasks  $n$ , because assigning each task to a single station results in a feasible solution as long as the necessary condition for feasibility ( $c \geq t_{max}$ ) is fulfilled (Scholl, 1999, 52). Other more sophisticated upper bounds exist and may better constrain the solution space and reduce the number of decision variables. For a detailed discussion of upper bounds on the number of stations see for

example Scholl (1999).

Different types of objective functions for the SALBP-1 have been proposed in the literature. A frequently used objective function, which is especially used in early approaches, penalizes the use of additional stations as for instance in Baybars (1986). An easier and more efficient objective function is proposed by Patterson and Albracht (1975) who introduce a fictitious sink in the precedence graph wherever the graph contains several original sinks. We assume that task  $n$  is such a unique sink. In this case the objective of minimizing the number of stations which has to be augmented to formulation (3.1) - (3.4) in order to formulate SALBP-1 can be stated as follows:

$$\text{Minimize } Z_1 = \sum_{j \in SI_n} j \cdot x_{nj} \quad (3.5)$$

This objective function minimizes the index of the station to which task  $n$ , which is assumed to be the unique sink of all tasks, is assigned to, since this is the latest station used. As a result of this, the total line length is minimized.

### **Minimizing the cycle time (SALBP-2)**

The SALBP-2 problem modifies SALBP-F such that the cycle time is minimized for a given number of stations. Hence, the former parameter  $c$  is introduced as a decision variable and formulation (3.1) - (3.4) has to be augmented by the objective of minimizing the cycle time  $c$ . This can be done easily as shown below:

$$\text{Minimize } Z_2 = c \quad (3.6)$$

In this variation of the SALBP the constraint (3.3) controls the cycle time, which is now a decision variable.

### **Maximizing the line efficiency (SALBP-E)**

The SALBP version, which seeks to find the optimal combination of the number  $m$  of stations and the cycle time  $c$  as well as a respective line balance is called SALBP-E since the line efficiency  $E = t_{sum}/(m \cdot c)$  is maximized. To formulate SALBP-E both former parameters  $c$  and  $m$  are introduced as decision variables and formulation (3.1) - (3.4) has to be augmented by the non-linear objective function of maximizing the line efficiency  $E$ .

### 3.1.3 Generalized assembly line balancing problems

Since the SALBP versions are all based on the set of limiting assumptions listed above, there has been a lot of effort in describing and solving more realistic generalized problems in order to close the gap between research and industrial practice (Baybars, 1986; Boysen, Fliedner, and Scholl, 2007; Scholl, 1999). Following the classification of Baybars (1986), these problems are subsumed under the term *generalized assembly line balancing* (GALB), since most models are directly based on their SALBP counterparts.

This section provides an overview of the most important extensions, especially for automated assembly lines and lines producing large products such as body shells of automobiles. Due to the high precision of machines, the assumption of deterministic processing times is usually satisfied. If only specialized machinery is used in the line, only a few peculiarities arise from the fact that operations are carried out by machines. (Boysen, Fliedner, and Scholl, 2008) However, since multi-purpose machines with automated tool-swaps are employed more frequently, some special characteristics of automated assembly lines have to be considered. Hence, a number of optimization models which are dedicated to the design of automated assembly lines have been developed.

### **Cost-oriented objective function**

As already mentioned, the installation of automated assembly lines requires large capital investments for the equipment. In addition to these investments, operating the line also causes short-term operating costs such as costs for material, wages, setup costs, inventory costs as well as incompleteness cost (Becker and Scholl, 2006; Scholl, 1999, 20). Therefore, the objective of cost minimization considerably gains in importance in optimization models for balancing automated assembly lines. This holds especially true when the balancing problem is connected with the decision problem of selecting processing or equipment alternatives. The equipment selection problem arises when processing alternatives exist. This problem will be discussed in more detail below. For instance, Graves and Lamar (1983) presented the first formulation for the design of automated flow-lines with the objective of performing the equipment selection and the assignment of assembly operations in such a way that total costs, consisting of capital costs, operating costs, and costs for load/unload operations, are minimized. Graves and Redfield (1988) subsequently extended this formulation such that tool change times and costs are considered. However, the balancing problem they consider is simplified by assuming a fixed sequence of operations (serial precedence graph).

### **Equipment selection and processing alternatives**

If there are several multi-purpose machines which can carry out a certain task with different performance (i.e., different processing times), processing alternatives need to be considered (Boysen, Fliedner, and Scholl, 2008). Hence, the assignment of operations to stations should be related to the selection problem of the equipment which is required to perform these operations (Becker and Scholl, 2006; Boysen, Fliedner, and Scholl, 2008). When the two problems of assigning operations and also the equipment to stations are considered simultaneously, the term

*assembly line design problem* is frequently used in the literature (Baybars, 1986). The assembly system design problem has received considerable attention. In the following we will briefly discuss a few research papers dealing with the equipment selection problem for automated assembly lines.

Rubinovitz, Bukchin, and Lenz (1993) were the first to provide a model for the robotic assembly line balancing problem (RALBP). They propose a formulation to allocate equal amount of work to the stations of the line while assigning the most efficient robot type to each station. Since it is assumed that all equipment types have the same installation costs, the length of the line (i.e., the number of stations) is minimized. Levitin, Rubinovitz, and Shnits (2006) present a genetic algorithm for the robotic assembly line balancing problem where different robots have to be assigned to the assembly tasks, and each robot needs different assembly times to perform a given task, because of its capabilities and specialization. The objective is to minimize the cycle time of an assembly line with a given number of stations. Bukchin and Rubinovitz (2003) present and discuss two problem formulations for minimizing the number of stations, and minimizing the total cost. Furthermore, they consider station paralleling, i.e. several stations are allowed to perform tasks in parallel. Pinnoi and Wilhelm (1998) propose an effective branch-and-cut approach for the single-model assembly system design problem. The model considers processing alternatives for the equipment choice with the objective of minimizing total cost. One equipment type from a predefined set of different equipment types has to be assigned to each station. Hence, two sub problems have to be solved: First, a varying number of stations has to be installed and provided with equipment. Then, the tasks have to be assigned to the stations considering station related assignment restrictions because some tasks can only be performed by a subset of the equipment types. Assignment restrictions, which are common for automated assembly lines, will be discussed in detail below. The same

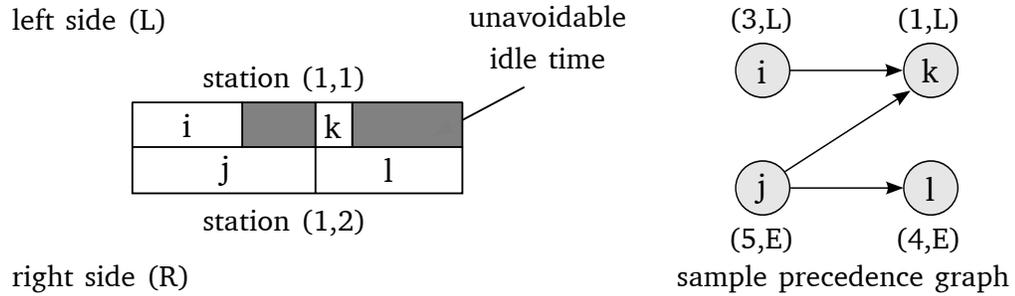
problem is considered by Bukchin and Tzur (2000) and Nicosia, Pacciarelli, and Pacifici (2002) who develop an optimal and heuristic algorithm and a dynamic programming algorithm, respectively.

### **Assignment restrictions**

Whenever some tasks can only be carried out by a subset of available machines as described above or cannot be performed on the same machine at all, assignment restrictions have to be considered. Furthermore, automated tool swaps may take a certain period of time which might further be dependent on the sequence of tasks. (Boysen, Fliedner, and Scholl, 2008) Therefore, Wilhelm (1999) augments the problem of the minimum-cost assignment of machines and tasks to stations by selecting the optimal sequence of operations at each station, including tool changes in order to address the problem of sequence-dependent setup costs. Another limiting factor when assigning tasks to a station is the capacity of the tool magazine which might be limited in size. In a family of hierarchical models for the design of assembly systems, Pinnoi and Wilhelm (1997) present a set of models that incorporate not only limited tool magazine capacity but successively more advanced features (e.g., multi-model production, linked/incompatible tasks which have to/cannot be assigned to the same station, processing alternatives, parallel stations, parallel working places within a station) with the ultimate goal to develop models that can be exploited by strong cutting plane methods.

### **Two-sided assembly line balancing**

Two-sided assembly lines are typically found wherever large products, such as automobiles, are assembled. The assembly tasks can be performed in parallel on both sides of the line. Therefore, two-sided assembly lines can provide the following advantages: shorter line length, reduced throughput time, lower cost of tools



**Figure 3.2:** Configuration of a two-sided assembly line. (Chutima and Chimklai, 2012)

and fixtures, and less material handling (Bartholdi, 1993). A pair of two directly facing stations, such as station (1, 1) and (1, 2), is called a mated-station, and one of them calls the other a companion. The main difference of two-sided ALB compared to traditional (one-sided) ALB is that tasks have a preferred operation direction. While some tasks prefer one of the two sides, others can be performed on either side of the line. Therefore, tasks are divided into different groups: L (left), R (right), and E (either)-type tasks. Due to the consideration of operation directions, precedence and cycle time restrictions have to be handled in a special way. In some situations idle times are unavoidable even between tasks that are assigned to the same mated station. Consider, for instance, the example in figure 3.2. Each task is associated with a label  $(t_i, d)$  where  $t_i$  is the processing time of task  $i$  and  $d$  ( $= L, R,$  or  $E$ ) is its preferred operation direction. Task  $k$  has two immediate predecessors, tasks  $i$  and  $j$ . After completion of task  $i$  on the left side of the line, task  $k$  cannot be started until task  $j$ , which is assigned to the right side of the line, is finished. Hence, two-sided ALB has to consider sequence-dependent finish time of tasks, unlike one-sided ALB.

Although two-sided assembly lines are found often in practice, little attention has been paid to these problems so far. Bartholdi (1993) was the first to address two-sided ALB: He proposed a simple assignment rule, and developed an interactive program as decision support for humans to build solutions quickly. The first math-

emathical formulation for two-sided ALB has been reported by Kim, Song, and Kim (2009).

### **Breakdowns of machinery**

So far only a few studies address the problem of balancing automated assembly lines while considering the machines to be unreliable. Wherever there is any recognition of machines to be unreliable, a respective placement and dimensioning of buffers is proposed. Buffers allow to throughput to be maintained in spite of breakdowns Hillier and So (1991); Tempelmeier (2003). According to Boysen, Flidner, and Scholl (2008) the lack of research on assembly line balancing problems considering breakdowns of machinery indicates that ALB misses the right instruments to attenuate the effects of breakdowns. However, Kahan et al. (2009) propose a backup strategy where working robots perform the tasks of failed robots during repair times. They present a mixed-integer formulation, which minimizes the throughput loss after a robot fails by utilizing the systems' redundancy. Each time a robot fails, the tasks originally assigned to this robot are reallocated such that the productivity loss is minimized. The reallocation is subject to precedence constraints as well as assignment restrictions. The assignment restrictions are due to the fact that each robot can only perform a certain set of operations. The capability of the robot to perform an operation is mainly determined by its tool configuration and physical location. In a large-scale discrete-event simulation model of an automotive body shop, which is based on a real-world example from General Motors, they demonstrate the efficiency of their approach.

### **3.2 Solution procedures for assembly line balancing problems**

Solution procedures for optimization problems are usually divided into two categories: exact and approximate procedures. Since even the most simplified line

balancing problem, the SALBP-F is proven to be an  $\mathcal{NP}$ -complete feasibility problem, i.e. the required computational time for exact procedures increases exponentially with the size of the instance considered, the optimization versions of SALBP are  $\mathcal{NP}$ -hard. (Wee and Magazine, 1982; Scholl, 1999, Chapter 2.2.1.5) Furthermore, the same is true for any relevant generalized problem. Hence, the application of exact solution procedures is usually limited to small test instances. To solve large-scale problems, a great amount of research concentrates on the development of approximate methods. In the following, both exact and approximate solution methods for line balancing problems will be presented, respectively.

### 3.2.1 Exact procedures

Exact procedures for line balancing problems can be either approaches implemented in a standard general solver (e.g., ILOG Cplex, ILOG Solver, Dash Xpress MP, LINGO, etc.) or originally dedicated solution methods. To solve line balancing problems using a standard general solver, an appropriate mathematical model for the problem needs to be defined and then the solver parameters are adjusted in order to solve the problem as quickly as possible. Most line balancing problems are defined using mixed integer programs (Battaïa and Dolgui, 2013). These problems are usually solved via the well-known *Branch and Bound* or *Branch and Cut* methods, which are implemented standard solvers.

However, since standard solvers are designed to cope with a great variety of different optimization problems, they may not be able to solve certain versions of line balancing problems within a reasonable time. In this case, original dedicated exact solution methods can be developed. (Battaïa and Dolgui, 2013) In the following we will discuss the dedicated exact solution methods which can be found most frequently in the literature.

## Problem-specific Branch and Bound procedures

Specific Branch and Bound procedures for line balancing problems make use of special lower bounds for the optimization problem. Therefore, a great number of sub-problems in the solution space can be excluded, which decreases the solution time dramatically. In the following we investigate the three most referenced specific Branch and Bound algorithms developed for the SALBP-1, namely FABLE, EUREKA and SALOME. Furthermore, the most recent Branch and Bound algorithm for the SALBP, which is currently the best exact solution procedure, will be described.

The Branch and Bound procedure is a frequently employed solution concept in combinatorial optimization and consists of the two main components *branching* and *bounding*. In addition to that, dominance and reduction rules can be used in order to improve the efficiency of the algorithm. During the branching process, the initial solution (root node) is divided into several sub-problems.

Generally, two different basic branching strategies can be distinguished for Branch and Bound procedures for the SALBP-1: task- versus station-oriented assignment. Task-oriented procedures iteratively choose a single task and add it to the next station to which it is assignable. Hence, each branch corresponds to the allocation of a single task at once. In contrast to this, station-oriented procedures build a complete station load for one station in each step. Hence, a branch corresponds to the total workload of a station in the station-oriented construction scheme. One drawback of the task-oriented assignment is that this procedure fills stations successively with tasks without controlling their final idle times. Therefore, the search can be less strictly directed to finding promising partial solutions as compared to the station-oriented assignment. (Scholl, 1999, 116-117)

Johnson (1988) developed a Branch and Bound algorithm, FABLE, for solving the

SALBP-1. FABLE is a depth-first search algorithm with a logic designed in a way that achieves feasibility quickly. Starting with the first workstation, sub-problems are constructed by adding a single assignable task to the current workstation. If no such task exists, a new workstation is used. Hence, this Branch and Bound algorithm is task-oriented, i.e. each branch corresponds to the allocation of a single task at once. Hoffmann (1992) developed another depth-first search algorithm, EUREKA, for solving the SALBP-1. In contrast to FABLE, this algorithm uses a station-oriented a construction scheme. Based on the main ideas of FABLE and EUREKA, Scholl and Klein (1997) proposed a new bi-directional Branch and Bound algorithm, namely SALOME, for the SALBP-1. Recently, Sewell and Jacobson (2012) developed a Branch, Bound, and Remember algorithm using memory to eliminate redundant sub-problems. This algorithm provides optimal solutions for 269 well-known test instances in less than half a second per problem, on average and is currently the best existing exact solution procedure for the SALBP-1. In addition to the Branch and Bound algorithms for the SALBP described above, a number of new methods, which can solve generalized problems, are also available.

In addition to problem-specific Branch and Bound algorithms, a few studies make use of *dynamic programming* to solve ALB problems. Dynamic programming is a method for solving large problems by breaking them down into smaller sub-problems, which are easier to solve. Then, the solution of the sub-problems are combined to reach an overall solution. (Cormen et al., 2009, 359) Dynamic programming for ALB problems is usually based on the constrained shortest path in a specific graph with partial solutions (Dolgui, Guschinsky, and Levin, 2006).

### **3.2.2 Approximate procedures**

Whenever large-scale instances have to be solved or the available time to generate a solution is strongly limited by the decision context, approximate methods

are inevitable. This still holds true despite the fact that some very efficient exact solution procedures have been developed as described above. The application of these methods is still limited to relatively small test instances in order to get benchmarks for the solutions generated by approximate procedures. While approximate procedures do not guarantee optimality, they are usually able to achieve good feasible results within acceptable computation time. Generally, approximate solution procedures are divided in: bounded exact methods, simple heuristics, and meta-heuristics.

### **Bounded exact methods**

This class of approximate procedures performs an incomplete enumeration of the solution space. Generally, these procedures can be obtained by bounding existing exact methods (see section 3.2.1) by means of heuristic rules, which restrict the searching space (Scholl and Becker, 2006; Battaïa and Dolgui, 2013). The first procedure of this class has been proposed by Hoffman (1963). This heuristic works unidirectionally in a station-oriented manner i.e., in each iteration  $k = 1, 2, \dots$  a load with minimum idle time is generated for station  $k$ . Hence, this procedure is a restricted Branch and Bound procedure.

### **Simple heuristics**

Simple heuristics can be further divided into single-pass and multi-pass heuristics. Single-pass heuristics assign tasks using a greedy function or priority rule in only one iteration. Hence, these methods can generate solutions in very short time even for large-scale problems. Multi-pass heuristics seek different assignments of tasks to stations in each pass of which the best solution is returned as output after a certain number of iterations. The tasks assigned to each station are selected randomly among a list of tasks having the greatest value of a greedy function.

The *Ranked Positional Weight* (RPW) procedure developed by Helgeson and Birnie (1961) is one of the best-known simple heuristics for the assembly line balancing problem. Each task is prioritized based on the cumulative assembly time with itself and its successors, i.e. its positional weight. In the next step tasks are assigned to stations in this order to the feasible workstation with the lowest index. The underlying idea is that the more tasks that are freed up and made eligible for assignment, the higher the likelihood of having a task available that fits in the remaining station idle time. (Askin and Standridge, 1993, 43) Simple heuristics are mainly used to provide upper bounds for the exact procedures described above or they are integrated into a metaheuristic for local improvements of intermediate solutions (Battaïa and Dolgui, 2013).

### **Metaheuristics**

Metaheuristics can be used for a great variety of optimization problems. While these methods are both numerous as well as varied they can be divided broadly into the following classes: neighborhood methods such as tabu search, evolutionary approaches such as genetic algorithms, and swarm-intelligence based approaches such as ant colony optimization. The most frequently used metaheuristic solution procedure for assembly line balancing problems is the *genetic algorithm*. Therefore, we will briefly discuss the underlying concept of this solution procedure.

The concept of genetic algorithms was developed by Holland (1975). Inspired by the the principles of natural selection and survival of the fittest, he showed that a computer simulation of this process of natural adaptation could be used for solving combinatorial optimization problems. Starting with an initial population of candidate solutions, different genetic operators such as mutation and crossover are applied to these solutions in order to generate new solutions. A fitness function is used to evaluate the candidate solutions. Based on the fitness values of the

solution candidates, a proportion of the existing population is selected to breed a new generation.

### **3.3 Evaluation of existing approaches**

As seen above, a great variety of optimization models for the configuration of assembly lines has been developed since the first formulation by [Salveson \(1955\)](#). Especially the stream of research on generalized assembly line balancing problems incorporated more and more aspects of real-world balancing problems in order to close the gap between the status of research and the requirements of real configuration problems. Furthermore, highly efficient solution procedures are available for both simple and generalized balancing problems, which allows solving large instances of assembly line balancing problems.

However, previous research in ALB has failed to address reliability issues in the configuration of assembly lines adequately despite increasing automation. If there is any recognition of machinery to be unreliable, a respective placement and dimensioning of buffers in the line is proposed. This approach seems to be a proper way to cope with unreliable machines due to the fact that buffers require only comparatively small investments. Hence, stations with unreliable machines are decoupled by buffers to attenuate the effect of breakdowns in most practical situations. Nevertheless, buffers do have several disadvantages: buffers lead to high operation as well as maintenance costs. Furthermore, buffers require much space on the shop floor and increase the overall lead time of the assembly system. ([Spieckermann et al., 2000](#)) Most notably, buffers increase the inventory, which is especially a relevant issue for pull-type production systems. Therefore, manufacturers try to use the least amount of buffering which is necessary in order to ensure the desired productivity rate.

Kahan et al. (2009) propose the first assembly line balancing formulation which accounts for machine breakdowns. They consider the problem of welding spot re-allocation due to robots' failures in an automotive body shop. Due to the very high level of automation in this stage of automotive plants, breakdowns of machinery become an important issue in the configuration of assembly lines in automotive body shops. This publication opens a very interesting and promising research path on how to cope with unreliable machinery. Each time a robot fails the groups of spots assigned to this robot will be reallocated to working robot(s). If no feasible solution exists, the groups of spots will be performed in a manual repair station at the end of the line. Hence, this problem can be interpreted as a rebalancing problem of an assembly line where the robots and groups of spots are analogous to the stations and tasks in the traditional assembly line, respectively.

Nevertheless, the formulation by Kahan et al. (2009) to handle robots' failures is restricted to the operational level of a production line, i.e. the robots are already placed in the line. Therefore, the robot capability matrix, which indicates whether a group of spots can be performed by a certain robot is already known and not part of the optimization. So far, the problem of configuring the line such that it is more robust against robots' failures has not been addressed. Hence, this thesis aims at developing an approach to configure assembly lines in automotive body shops such that the level of redundancy is maximized. The detailed discussion of this approach will be presented in the following chapter.

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## Chapter 4

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### **An approach for fault-tolerant flow-line design in automotive body shops**

After discussing existing optimization models for simple as well as generalized assembly line balancing problems, we show that despite increasing automation previous research in this field has failed to address the issue of balancing automated lines with unreliable machines although a great body of literature in the field of ALB has evolved since the first mathematical formulation of this problem. If there was any recognition of machines to be unreliable, a respective placement and dimensioning of buffers was proposed after configuring the line rather than considering unreliable machines in the design and configuration of the line. This approach is not entirely satisfactory, especially when considering highly automated pull-type production systems. One industry, which has been traditionally highly automated is the automotive industry. Especially the assembly lines in automotive body shops are characterized by robots' failures, which either result in stoppages of the line or in manual backup of the tasks. Since the problem of configuring automotive body assembly lines such that they are more robust against robots' failures has not been addressed so far, the aim of this chapter is to develop an optimization model for fault-tolerant flow-line design in automotive body shops.

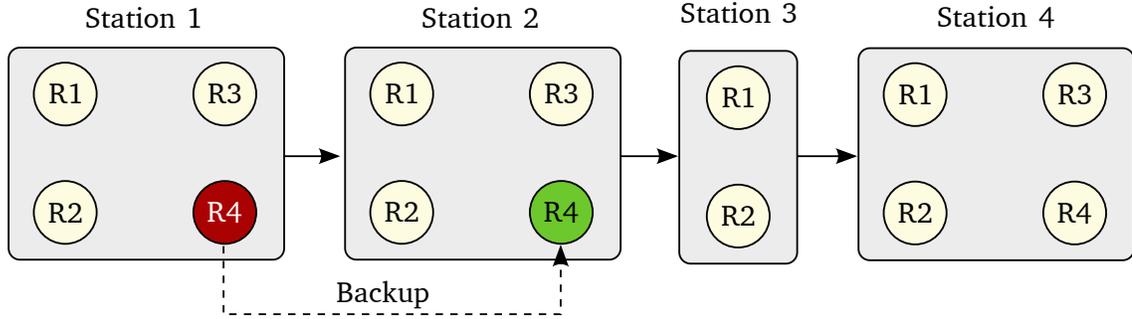
This chapter is organized as follows. First, a detailed description of the problem considered is given in section 4.1. Then, we give an overview on our approach along with the assumptions underlying the model formulation in 4.2. Finally, the mathematical formulation of our approach is presented in 4.3.

#### 4.1 Problem description

As discussed in chapter 2, body shops in the automotive industry consist of several robotic cells (referred to as stations) connected via a conveyor belt. Each station contains several robots that are working simultaneously on the body shells flowing down the line. The welding spots are grouped based on their location at the body shell and assigned to the robots in the stations, which perform them sequentially. Each robot can either perform a single group of spots or multiple groups of spots during one cycle. The processing time required for the welding operation consists of the time the robot needs to move from the “Home position” to the locations of the welding spots and back to the “Home position”, in addition to the time required to perform each spot.

Two different types of stations can be distinguished: geometric stations and respot stations. In geometric stations performing dimensional control welds (DCWs) new parts are assembled to the vehicle’s body to define a new geometry. Hence, a material handling system is required for feeding these stations with the new parts. On the other hand, respot stations only perform RSPs on the existing geometry - no new part is assembled - with the sole purpose of strengthening the body shell.

The problem considered here refers to the situation depicted in figure 4.1, in which robot R4 in the first station fails during the operation time and is replaced by robot R4 in the second station during the repair period. The selection of a backup robot is made such that the productivity loss during the repair period is minimized. This problem of selecting which robot(s) should replace the failed robot(s) during the repair period has been addressed by [Kahan et al. \(2009\)](#). However, they assume that the capability of each robot in terms of the welding spots it can perform is known in advance.



**Figure 4.1:** Problem illustration: robot R4 in station 1 fails and is backed up by robot R4 in station 2.

The capability of a robot to become a backup robot mainly depends on its welding gun configuration and its physical location. The former determines which operations can be performed and the latter defines the robots' work envelope. The capability of the machine remains unchanged as long as no technological changes are applied. (Kahan et al., 2009) Furthermore, we assume that only robots performing RSPs can be backed up. This is due to the fact that the required material handling system for geometric stations prevents that these robots can be backed up in a downstream station.

As the number of robots that are capable of performing a certain operation increases, the flexibility of the system also increases resulting in improved cycle times during robots' failures. This is due to the fact that the amount of work assigned to the failed robot can be reallocated to more robots. Based on simulation results Kahan et al. (2009) show that the systems' level of redundancy directly influences the cycle time, i.e. the higher the systems' level of redundancy the lower is the productivity loss in the event of robots' failures. Nevertheless, the problem of configuring the line such that the redundancy is maximized, has not been addressed yet. Hence, we propose an approach, in which welding guns are assigned to robots such that the cycle time is minimized while the redundancy of the system is maximized.

## 4.2 Overview and preliminaries

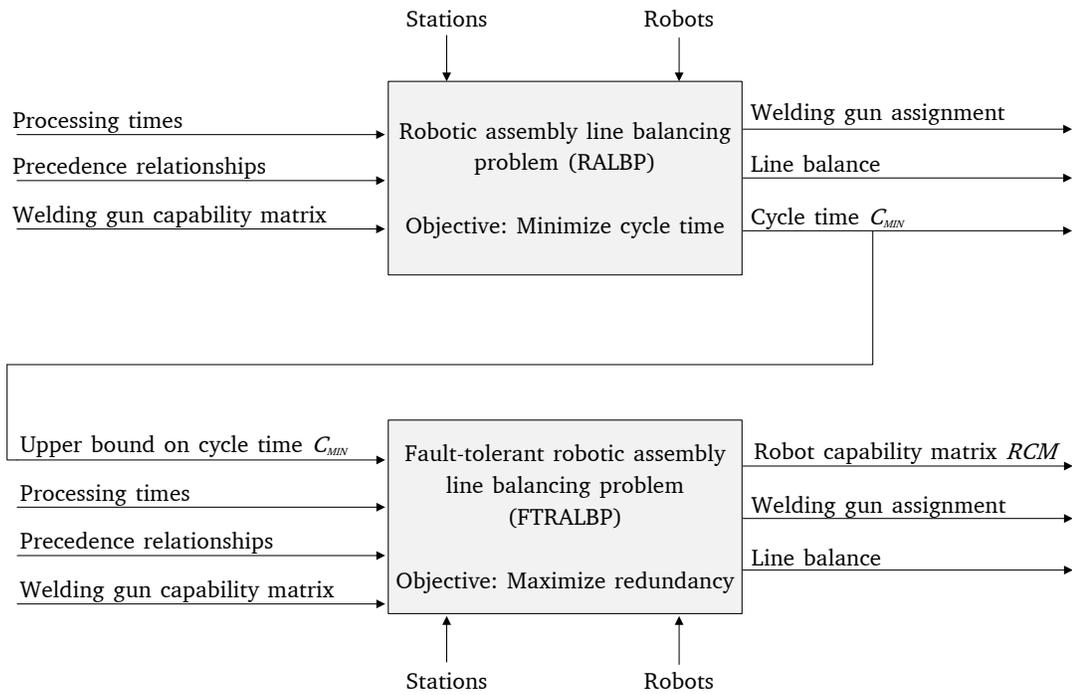
The generalized assembly line balancing problems for automated assembly lines and lines producing large products, which are described in section 3.1.3 serve as the basis for our approach. Aspects of existing approaches for balancing robotic assembly lines with the objective of minimizing the cycle time (RALBP-2) will especially be used in our model. Minimizing the cycle time is one of the primary objectives used in robotic assembly line balancing problems. This is due to the fact that in robotic assembly lines there is almost no variation from the established operation processing times. Consequently, any imbalance of the line will result immediately in idle times of the robots at certain workstations and will therefore reduce the systems' performance (Rubinovitz, Bukchin, and Lenz, 1993). Hence, our main objective is to minimize the cycle time of the robotic line. Given a fixed number of welding robots in a fixed number of workstations, achieving this objective maximizes the production rate and minimizes the robots' idle times. At the same time we want to maximize the systems' level of redundancy in order to make the line more robust against robots' failures. Consequently, a multi-objective optimization problems arises.

Different methods exist for solving multi-objective line balancing problems. For instance, the *aggregation of objectives* into a single objective function, usually by using a weighted sum, is frequently used. However, for such methods, the final solution depends on the weights which have to be specified. Furthermore, the complexity of the model increases dramatically due to the fact that all aspects regarding the different objectives have to be integrated in a single model. Another method called *lexicographic resolution* is based on an order of decision criteria (first criterion, second criterion etc.). Low priority objectives will only be optimized as far as they do not interfere with the optimization of higher priority objectives.

In our approach we use the idea of lexicographic resolution, by decomposing our problem into two sub-problems. Since we assume that the assembly line will remain in a state in which all robots are up for the majority of the time, the systems' redundancy should only be optimized as long as the initial cycle time is not affected. Consequently, we first solve the problem of configuring the line such that the cycle time is minimized. In the following we will refer to this model as robotic assembly line balancing problem (RALBP), because this formulation is based on formulations for the configuration of robotic lines that exist in the literature. As a result, we obtain the minimum cycle time for a given number of stations and robots as well as the operations which have to be assigned. In a second step we solve another model to maximize the systems' level of redundancy. This model is referred to as fault-tolerant robotic assembly line balancing problem (FTRALBP), because this formulation seeks for a configuration which is more robust against robot failures. This line balancing problem is restricted to the minimum cycle time from the RALBP. The relationships between the models, their data requirements and outputs are illustrated in figure 4.2.

We extend the common RALBP-2 model with the features, which are discussed in the following. To consider that each station in automotive body assembly lines usually consists of several robots working simultaneously on both sides of the line, we will integrate aspects of models for two-sided assembly line balancing problems where operations are performed in parallel at both sides of the line. We assume that each station contains four robots.

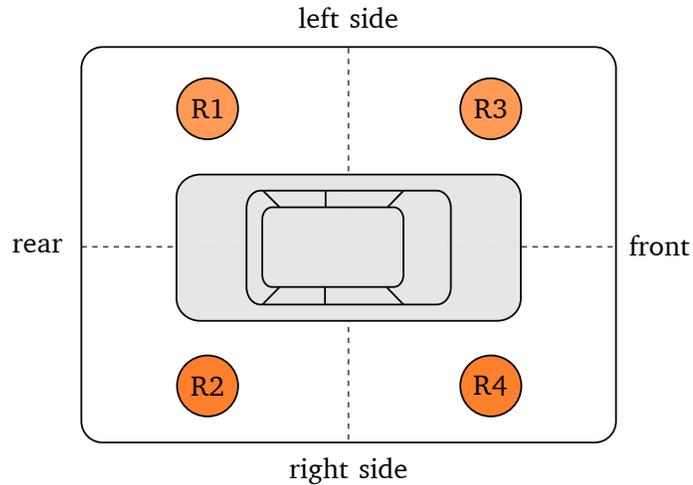
The groups of welding spots have restrictions with regard to the operation directions. Some groups of spots have to be performed on the right side of the line (e.g., right body-side) while others have to be performed on the left side of the line (e.g., left body-side). Furthermore, some groups of spots can be performed on either side



**Figure 4.2:** Relationships between the models, their data requirements and outputs.

of the line. In addition to the side of the line, we also have to consider that some groups of spots can only be performed in a front position within the station while others can only be performed in a rear position within the station. Additionally, some groups can be performed in either position within the station. Figure 4.3 shows the layout of a station with four robots. Note that robots on the left side have an odd index while robots on the right side have an even index. Moreover, robots in a rear position are indicated by an index of one or two while robots in a front position have an index of three or four.

The capability of each robot to perform a certain operation, which is captured by the robot capability matrix (RCM), is introduced as a new decision variable in our formulation. This capability depends on several factors which are discussed in the following.



**Figure 4.3:** Station layout.

(1) Most notably, the robot has to be equipped with a welding gun, which is capable of performing the location of the group of spots as it may not be possible for a particular welding gun to reach every location due to its geometry. The capability of a welding gun to perform a group of spots is captured by the welding gun capability matrix (WCM). (2) Furthermore, the physical location of the robot, i.e. the side of the line as well as the position within the station, affects its capability to perform a certain group of spots. For instance, a robot on the left side of the line can only perform groups of spots that have to be performed on the left side or groups which can be performed on either side of the line. (3) Finally, a backup robot should be located in a station that is downstream of the station to which the group of spots is originally assigned to. The motivation for the downstream condition is that downstream stations can backup the entire groups of a failed robot since the time of failure whereas backup by a robot in an upstream station requires manual backup for all the bodies that are in between the backup station and the station with the failed robot. Since manual backup results in inferior product quality and lower productivity compared to robotic backup, the use of the manual repair station should be minimized.

Before presenting the mathematical formulation, we introduce the notation used. Each group of spots  $i$  has to be allocated to one of the robots  $r$  located in the stations  $k$  in the line. The set of groups of spots is divided into several subsets, depending on the operation position and direction. Each subset of groups of spots is associated with a label  $(I_{p,d})$  where  $p$  is its position within the station (= rear (R), front (F), or either (E)), and  $d$  (= left (L), right (R), or either (E)) is its operation direction.

When allocating the different groups of spots to robots in the stations of the line precedence relations between the groups have to be considered. The immediate predecessors of a group of spots  $i$ , are captured in the set  $IP_i$ . Precedence relationships mainly result from the product structure along with the characteristics of the production system. For instance, a precedence constraint may result if during the assembly process the access to a specific location in the body is avoided due to its covering by a welded part. However, it should be noted that a common precedence graph for an automotive body provides a high degree of flexibility due to the fact that the majority of welding operations are RSPs, i.e. no new parts are assembled. We assume that the different subsets of groups of spots are not restrictive with each other in terms of precedence relations, i.e., precedence relationships only exist within the different subsets of groups of spots. As a result, sequence-dependent finish times do not have to be considered. All sets and indices are summarized below.

*Sets and indices:*

$I$  = set of all groups of spots ( $i = 1, 2, \dots, I$ )

$I_{R,L}$  = set of groups that have to be done in a rear position on the left side

$I_{R,R}$  = set of groups that have to be done in a rear position on the right side

$I_{F,L}$  = set of groups that have to be done in a front position on the left side

$I_{F,R}$  = set of groups that have to be done in a front position on the right side  
 $I_{R,E}$  = set of groups that have to be done in a rear position on either side  
 $I_{F,E}$  = set of groups that have to be done in a front position on either side  
 $I_{E,L}$  = set of groups that have to be done in on the left side in either position  
 $I_{E,R}$  = set of groups that have to be done in on the right side in either position  
 $J$  = set of welding guns ( $j = 1, 2, \dots, J$ )  
 $K$  = set of stations ( $k = 1, 2, \dots, K$ )  
 $R$  = set of robots ( $r = 1, 2, \dots, R$ )  
 $R_{k,r}$  = the  $r^{th}$  robot in the  $k^{th}$  station  
 $IP_i$  = set of immediate predecessors of task  $i$

Prior to implementing the formulation, the welding gun capability matrix as well as the process times of the groups of spots should be obtained. Each element  $WCM_{ij}$  of the welding gun capability matrix is equal to one if the group of spots  $i$  can be performed by the welding gun  $j$  and zero otherwise. The welding gun capability matrix can be obtained by analyzing CAD data of the body shell in order to identify which welding gun can reach to certain welding locations based on its geometry. The processing times of the groups of spots mainly depend on the number of spots in the group. Furthermore, the distances between the spots as well as the welding time for each spot affect the processing time. In addition to these input parameters, we will make use of a very large positive number,  $M$  in order to control when certain constraints become active. The input parameters of the formulation are summarized below. For the second formulation the minimum cycle time,  $C_{min}$ , obtained by solving the first formulation is used as a parameter to ensure that the redundancy is only maximized as long as the minimum cycle time is not exceeded.

*Input parameters:*

$t_i$  = Process time of group of spots  $i$

$C_{min}$  = Minimum cycle time

$M$  = Very large positive number

$$WCM_{ij} = \begin{cases} 1, & \text{if group of spots } i \text{ can be performed by welding gun } j \\ 0, & \text{otherwise.} \end{cases}$$

Minimizing the cycle time is a frequently used objective in many ALB formulations. Since our first formulation, the RALBP, also aims at minimizing the cycle time (or maximizing the productivity loss) we use the cycle time  $C$  as a decision variable for this model. The cycle time depends on the assignment of groups of spots  $i$  to the different robots, because it is determined by the robot with the highest load. The allocation of groups of spots to robots is captured by the binary assignment variable  $x_{ikr}$ . The assignment variable  $x_{ikr}$  is equal to one when a group of spots  $i$  is assigned to robot  $r$  in station  $k$  and zero otherwise. As discussed above, different welding guns can be assigned to the robots. To capture the assignment of welding guns to robots, we introduce another binary variable  $y_{jkr}$ . This variable is equal to one if welding gun  $j$  is assigned to robot  $r$  in station  $k$  and zero otherwise. Consequently, this variable determines which groups of spots can be performed by a certain robot with regard to the WCM. Finally, we introduce the robot capability matrix,  $RCM_{ikr}$ , as a new decision variable in our second formulation, the FTRALBP. Each element  $RCM_{ikr}$  of the robot capability matrix is equal to one if the group of spots  $i$  can be performed by robot  $r$  in station  $k$  and zero otherwise. Whether an entry  $RCM_{ikr}$  is equal to one depends on the welding gun configuration as well as the physical location of the robot. The decision variables used in the formulation are summarized below.

*Decision variables:*

$C$  = cycle time of the system

$$x_{ikr} = \begin{cases} 1, & \text{if group of spots } i \text{ is assigned to robot } r \text{ in station } k \\ 0, & \text{otherwise.} \end{cases}$$

$$y_{jkr} = \begin{cases} 1, & \text{if welding gun } j \text{ is assigned to robot } r \text{ in station } k \\ 0, & \text{otherwise.} \end{cases}$$

$$RCM_{ikr} = \begin{cases} 1, & \text{if group of spots } i \text{ can be performed by robot } r \text{ in station } k \\ 0, & \text{otherwise.} \end{cases}$$

### 4.3 Mathematical formulations

The goal of this section is to provide an approach to configure the assembly line of an automotive body shop such that the cycle time of the system is minimized and the systems' level of redundancy is maximized. As discussed above, our approach contains two formulations, which are solved sequentially. Using the introduced notation, we will derive the two formulations. Both formulations are discussed in the following.

#### **Robotic assembly line balancing problem:**

The first formulation presented finds a line balance, which provides the minimum cycle time. Although this formulation is mainly based on formulations for the configuration of robotic lines that exist in the literature, we augment these formulations such that we can balance a line with several robots within each station.

The mathematical model is given in (4.1) - (4.16). The aim of the model is to equip all robots with welding guns and assign all groups of spots to feasible robots such that the initial cycle time is minimized. We emphasize that this is only the initial

cycle time of the system. As the systems' state changes, i.e. robots are offline, the cycle time may increase due to the reallocation of groups of spots. The objective function (4.1) which seeks to minimize the initial cycle time (or maximize the productivity) is shown below.

$$\text{Minimize } C \tag{4.1}$$

In the following we will present all of the constraints required for the initial assignment of the groups of spots to robots, i.e. all groups are assigned to feasible robots and precedence relationships between groups are considered. Constraints (4.2), also referred to as occurrence constraints, ensure that each group of spots is assigned exactly once to one of the robots in the system.

$$\sum_{k=1}^K \sum_{r=1}^R x_{ikr} = 1 \quad \forall i \in I \tag{4.2}$$

Constraints (4.3) ensure that each robot in the system is equipped with exactly one welding gun. Despite the fact that modern robots can change their tools within five to ten seconds allowing changeovers with relatively short setup times, most robots in respot cells are usually equipped with only one welding gun.

$$\sum_{j=1}^J y_{jkr} = 1 \quad \forall k \in K, r \in R \tag{4.3}$$

Constraints (4.4) assure that each group of spots is assigned to a feasible robot with respect to its welding gun configuration. Only those groups of spots, which can be reached by the welding gun assigned to a certain robot, can be allocated to this robot.

$$x_{ikr} \leq \sum_{j=1}^J y_{jkr} \cdot WCM_{ij} \quad \forall i \in I, k \in K, r \in R \tag{4.4}$$

Constraints (4.5) ensure that precedence relations between the different groups of spots are considered. A group of spots  $h$  which is an immediate predecessor of the group of spots  $i$  has to be assigned to the same or an earlier station in the line for a feasible line configuration.

$$\sum_{l=1}^L \sum_{r=1}^R x_{hlr} \cdot h \leq \sum_{k=1}^K \sum_{r=1}^R x_{ikr} \cdot k \quad \forall i \in I, h \in IP(i) \quad (4.5)$$

Constraints (4.6) calculate the systems' cycle time, which is determined by the robot in the line with the highest load. Constraints (4.2) - (4.6) are commonly found in other ALB models for robotic lines that exist in the literature.

$$\sum_{k=1}^K \sum_{r=1}^R x_{ikr} \cdot t_i \leq C \quad \forall i \in I \quad (4.6)$$

The following constraints (4.7) - (4.14) ensure that the different subsets of tasks are assigned to a feasible robot with regard to its position within the station (rear, front, either) as well as the side of the line (left, right, either). Constraint set (4.7) ensures that all groups of spots, which have to be performed on the left side but can be performed in either position ( $I_{E,L}$ ), are assigned to a robot with an odd index.

$$\sum_{k=1}^K \sum_{r=1}^R x_{ikr} \cdot r \bmod 2 = 1 \quad \forall i \in I_{E,L} \quad (4.7)$$

This is done by using the modulo operation (also referred to as modulus), which finds the remainder of division of one number by another. Given two positive integers,  $r$  the index of the robot and the dividend as well as the even number 2 as the divisor, the modulo operation would evaluate the expression " $r \bmod 2$ " to one or zero for an odd or even index of  $r$ , respectively.

The idea of using the modulo operation for assigning groups of spots to the right side is also used in constraint set (4.8). This constraint ensures that all groups of spots, which have to be performed on the right side but can be performed in either

position ( $I_{E,R}$ ), are assigned to a robot with an even index.

$$\sum_{k=1}^K \sum_{r=1}^R x_{ikr} \cdot r \bmod 2 = 0 \quad \forall i \in I_{E,R} \quad (4.8)$$

Constraints (4.9) ensure that those groups of spots, which have to be performed on the rear but can be done on either side of the line ( $I_{R,E}$ ) are assigned to a robot with an index less than or equal to two, i.e. a rear position within the station.

$$\sum_{k=1}^K \sum_{r=1}^R x_{ikr} \cdot r \leq 2 \quad \forall i \in I_{R,E} \quad (4.9)$$

Similarly, constraints (4.10) assure that those groups of spots, which have to be performed on the front but can be done on either side of the line ( $I_{F,E}$ ) are assigned to a robot with an index greater than or equal to three, i.e. a front position within the station.

$$\sum_{k=1}^K \sum_{r=1}^R x_{ikr} \cdot r \geq 3 \quad \forall i \in I_{F,E} \quad (4.10)$$

Constraints (4.11) ensure that those groups of spots, which have to be performed on the rear and have to be done on the left side of the line ( $I_{R,L}$ ) are assigned to a robot with an index equal to one, i.e. a rear position within the station on the left side of the line.

$$\sum_{k=1}^K \sum_{r=1}^R x_{ikr} \cdot r = 1 \quad \forall i \in I_{R,L} \quad (4.11)$$

Similarly, constraints (4.12) ensure that those groups of spots, which have to be performed on the rear and have to be done on the right side of the line ( $I_{R,R}$ ) are assigned to a robot with an index equal to two, i.e. a rear position within the station on the right side of the line.

$$\sum_{k=1}^K \sum_{r=1}^R x_{ikr} \cdot r = 2 \quad \forall i \in I_{R,R} \quad (4.12)$$

Constraints (4.13) assure that those groups of spots, which have to be performed on the front and have to be done on the left side of the line ( $I_{F,L}$ ) are assigned to a robot with an index equal to three, i.e. a front position within the station on the left side of the line.

$$\sum_{k=1}^K \sum_{r=1}^R x_{ikr} \cdot r = 3 \quad \forall i \in I_{F,L} \quad (4.13)$$

Constraints (4.14) assure that those groups of spots, which have to be performed on the front and have to be done on the right side of the line ( $I_{F,R}$ ) are assigned to a robot with an index equal to four, i.e. a front position within the station on the right side of the line.

$$\sum_{k=1}^K \sum_{r=1}^R x_{ikr} \cdot r = 4 \quad \forall i \in I_{F,R} \quad (4.14)$$

Constraint set (4.15) defines the assignment variables for both groups of spots as well as welding guns to the stations and robots as binary.

$$x_{ikr}, y_{jkr} \in \{0, 1\} \quad \forall i \in I, j \in J, k \in K, r \in R \quad (4.15)$$

Finally constraint (4.16) ensures non-negativity of the cycle time.

$$C \geq 0 \quad (4.16)$$

Solving the formulation presented above, the initial assignment of groups of spots to robots can be done. As a result, we obtain the minimum cycle time, which is possible for a given set of groups of spots, welding guns, stations and robots. However, the novelty of our approach is the consideration of the capability of a robot to perform groups of spots other than those initially assigned to it, i.e. the systems' redundancy. The problem of maximizing the systems' redundancy is presented in the following.

### Fault-tolerant robotic assembly line balancing problem:

In order to maximize the systems' level of redundancy we maximize the sum over all of the entries in the robot capability matrix  $RCM_{ikr}$ . This is done in the objective function (4.17).

$$\text{Maximize } \sum_{i=1}^I \sum_{k=1}^K \sum_{r=1}^R RCM_{ikr} \quad (4.17)$$

The objective of maximizing the systems' level of redundancy is also restricted to constraints (4.2) - (4.5) and (4.7) - (4.14). Additionally, the following constraints have to be taken into account.

In order to assure that the systems' level of redundancy is only maximized as long as the minimum cycle time obtained by solving the RALBP presented above is not exceeded, constraint (4.18) restricts the load of any robot to be less than or equal to the minimum cycle time  $C_{min}$ .

$$\sum_{i=1}^I x_{ikr} \cdot t_i \leq C_{min} \quad \forall k \in K, r \in R \quad (4.18)$$

To ensure that the entries of the robot capability matrix,  $RCM_{ikr}$  will be equal to one if a robot meets all the requirements to become a backup robot and zero otherwise we subject the problem of maximizing the systems' level of redundancy to the constraints (4.19) - (4.24). Above all, a robot has to be equipped with a feasible welding gun in order to become a backup robot for a certain group of spots  $i$ . Therefore, constraint (4.19) checks whether robot  $r$  can perform group of spots  $i$  based on its welding gun configuration. Only if a robot  $r$  is equipped with a feasible welding gun  $j$ , does its entry  $RCM_{ikr}$  become one and otherwise it becomes zero.

$$RCM_{ikr} \leq \sum_{j=1}^J WCM_{ij} \cdot y_{jkr} \quad \forall i \in I, k \in K, r \in R \quad (4.19)$$

Furthermore, all groups of spots, which have to be performed on the left side, i.e.  $I_{R,L}$ ,  $I_{F,L}$ , and  $I_{E,L}$ , can only be performed by a robot, which is located on the left side of the line. Hence, we use the modulo operation again in order to ensure that an entry  $RCM_{ikr}$  for a group of spots  $i$  that has to be performed on the left side of the line can only become one if this robot is located on the left side. Constraints (4.20) ensures that an entry  $RCM_{ikr}$  for a group of spots  $i$  that has to be performed on the left side of the line becomes zero for any robot which is located on the right side of the line. This is due to the fact that the modulo operation would evaluate the expression “ $r \bmod 2$ ” to zero for any robot with an even index, i.e., a robot on the right side of the line.

$$RCM_{ikr} \leq \sum_{j=1}^J y_{jkr} \cdot r \bmod 2 \quad \forall i \in I_{R,L} \cup I_{F,L} \cup I_{E,L}, k \in K, r \in R \quad (4.20)$$

Similarly, constraints (4.21) ensures that an entry  $RCM_{ikr}$  for a group of spots  $i$  that has to be performed on the right side of the line, i.e.  $I_{R,R}$ ,  $I_{F,R}$ , and  $I_{E,R}$ , becomes zero for any robot which is located on the left side of the line. Again, the modulo operation would evaluate the expression “ $r \bmod 2$ ” to zero for any robot with an even index, i.e., a robot on the right side of the line allowing the left side of the constraint to become equal to one.

$$RCM_{ikr} \leq 1 - \left( \sum_{j=1}^J y_{jkr} \cdot r \bmod 2 \right) \quad \forall i \in I_{R,R} \cup I_{F,R} \cup I_{E,R}, k \in K, r \in R \quad (4.21)$$

Constraints (4.22) assure that all groups of spots which have to be performed in a rear position, i.e.  $I_{R,R}$ ,  $I_{R,L}$ , and  $I_{R,E}$ , can only be backed up by a robot located in a rear position. An entry  $RCM_{ikr}$  for a group of spots  $i$  which has to be performed in a rear position can only be equal to one if the robot is located in a position with an index less than or equal to two. Whenever the index of the robot  $r$  is greater than 2, the entry  $RCM_{ikr}$  becomes zero in order to satisfy the constraint, which is

done using a very large positive integer,  $M$ .

$$\sum_{j=1}^J y_{jkr} \cdot r \leq 2 + (1 - RCM_{ikr}) \cdot M \quad \forall i \in I_{R,R} \cup I_{R,L} \cup I_{R,E}, k \in K, r \in R \quad (4.22)$$

Constraints (4.23) ensure that all groups of spots, which have to be performed in a front position, i.e.  $I_{F,R}$ ,  $I_{F,L}$ , and  $I_{F,E}$ , can only be backed up by a robot located in a front position within the station. An entry  $RCM_{ikr}$  for a group of spots  $i$  which has to be performed in a front position can only be equal to one if the robot is located in a position with an index greater than or equal to three. Whenever the index of the robot  $r$  is less than 3, the entry  $RCM_{ikr}$  becomes zero in order to satisfy the constraint, which is again done using a very large positive integer,  $M$ .

$$\sum_{j=1}^J y_{jkr} \cdot r \geq 3 - (1 - RCM_{ikr}) \cdot M \quad \forall i \in I_{F,R} \cup I_{F,L} \cup I_{F,E}, k \in K, r \in R \quad (4.23)$$

Constraints (4.24) ensure that a backup robot has to be located downstream from the station where the group of spots has been originally assigned. An entry  $RCM_{ikr}$  for a group of spots  $i$  can only be equal to one if the backup robot is assigned to a station with a greater index than the station to which groups were initially assigned. This is done to ensure that all groups following the failure can be backed up. In contrast, all body shells in between the station with the failed robot and an upstream backup station would require manual repair at the end of the line resulting in inferior quality.

$$\sum_{k=1}^K \sum_{r=1}^R x_{ikr} \cdot k \leq \left( \sum_{j=1}^J y_{jlt} \cdot l \right) + (1 - RCM_{ilt}) \cdot M \quad \forall i \in I, l \in K, t \in R \quad (4.24)$$

Finally, constraint set (4.25) defines the assignment variables for both groups of spots as well as welding guns to the stations and robots as well as the entries of the robot capability matrix as binary.

$$x_{ikr}, y_{jkr}, RCM_{ikr} \in \{0, 1\} \quad \forall i \in I, j \in J, k \in K, r \in R \quad (4.25)$$

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## Chapter 5

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### Numerical analysis

In the previous chapter we developed an approach for fault-tolerant design of body assembly lines in the automotive industry. In this chapter we present a numerical analysis to evaluate our approach. The numerical analysis in this chapter has two main objectives. Above all, we want to investigate the performance of our approach as compared to a benchmark that does not take into account the systems' level of redundancy. We will analyze if and to what extent our approach outperforms the benchmark. Furthermore, we want to identify operating conditions for which the approach is particularly well suited. This is important in order to gain insights on which factors promote or hinder the effectiveness of our approach and should therefore be considered during implementation. To account for the stochastic nature of the industrial environment which has not been considered in the mathematical formulation, we use a discrete-event simulation model of an automotive body shop.

This chapter is organized as follows. First, we will provide a detailed overview of the test environment, i.e. we will explain the goals of our study, present the setting and data for the numerical analysis and finally describe the evaluation criteria for the analysis in section 5.1. Then, we move on to discuss the results of our simulation experiments in detail in section 5.2. Finally, we draw conclusions in section 5.3 based on the results obtained in the study.

## **5.1 Definition of the test environment**

There exist several examples of body shop lines of different original equipment manufacturers (OEMs) in the literature (see e.g., [Naitoh et al. \(1997\)](#)). However, these examples only describe the general layout of the body shop while no details about the number of spot welds per station and the assignment of spot welds to robots are mentioned. Hence, there is not enough empirical data from industrial practice to model a real-world body shop line. Consequently, our data is based on information about body shop lines which can be found in different studies. Whenever the available data is not sufficient we will make reasonable assumptions about the system properties. The same holds true for details about the assembly structure for welding operations on automotive body shells. Although there exists a broad stream of literature on assembly line balancing in the automotive industry, no precedence graphs for the body shells of automobiles are reported. This is due to the fact that most studies in this field focus on balancing assembly lines in the last stage of automotive plants, the final assembly. As a result of this, we will also make reasonable assumptions for the structure of the precedence graph. Consequently, the results obtained in this numerical study are only partially transferable to real-world body shop systems. However, the simulation model is adequate for the objectives of this numerical study which are explained in detail in the next section.

### **5.1.1 Objectives and design of the study**

The objectives of our numerical analysis are twofold. Above all we want to investigate the performance of our approach which aims at configuring the line such that maximum redundancy is provided against a benchmark, i.e. the traditional approach for robotic assembly line balancing, which disregards robots' failures.

Furthermore, we are interested in gaining insights for operating conditions where our approach is particularly well suited. Therefore, we propose the following procedure.

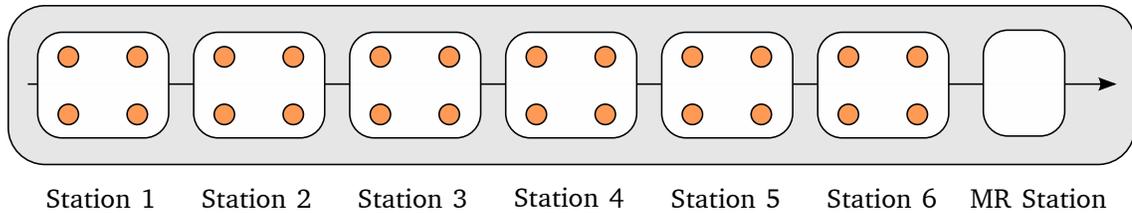
The benchmark is defined by the formulation that we use to obtain the minimum cycle time. This formulation only uses information on the precedence relations and the welding guns capability matrix to find a line balance that provides the minimum cycle time for a given number of robots in the line. Based on the line balance obtained using this formulation we compute the corresponding robot capability matrix RCM afterwards. This RCM is compared with the one we obtain using our approach which seeks to maximize the systems' level of redundancy.

Although the proposed formulations can be solved to optimality, we can only observe the level of redundancy in the system obtained by the different approaches. However, we cannot make any conclusions on how the different approaches affect important performance measures such as the cycle time in an automotive body shop. Therefore, we solve the general robot backup formulation presented by [Kahan et al. \(2009\)](#) (see section 3.1.3) with the different capability matrices as an input parameter. The full mathematical formulation from [Kahan et al. \(2009\)](#) in accordance with the notation used in this thesis is presented in appendix A. Their approach focuses on a particular system state after a failure occurs and aims at finding the best backup solution for this occurrence. Therefore, a direct comparison of our approach with the benchmark is still not possible, because at this stage we could only compare the performance for each possible state of the system. In a real-world setting, robot failures occur randomly over time and the repair time is a random variable. Furthermore, the number of robots failing simultaneously may change. To account for these stochastic effects, a simulation model is employed in order to evaluate the performance of the two approaches.

Consequently, we implemented a discrete-event simulation model of an automotive body shop with the simulation software package Anylogic. Each time a robot state is changed, an a priori generated solution is generated. Therefore, no communication between the optimization software and the simulation model is necessary, because the allocations of groups of spots to robots for all possible states are already generated and can be loaded from the database whenever the systems' state changes. For each failure scenario two options arise. If a feasible solution exists, the groups of spots initially allocated to the failed robot are reallocated to one or more backup robots. If no feasible solution exists, the groups are reallocated to a manual repair (MR) station at the end of the line. As described in section 2.2.2 virtually all body assembly lines have a such a backup station at the end of the line in order to backup operations while robots are offline. Like [Kahan et al. \(2009\)](#), we assume that the allocation the MR station is always possible as a last resort when no robotic backup exists, regardless of the precedence constraints.

The number of possible scenarios which have to solved a priori depends on the number of robots that are prone to failure. For instance, when two out of twenty-four robots can fail simultaneously, the total number of failure scenarios which have to solved is  $\binom{24}{1} + \binom{24}{2} = 300$ . From the simulation we finally collect statistics to evaluate our approach. The evaluation criteria that we used are described in detail in section 5.1.3.

Since the focus of this thesis is not on solution methodology for the proposed formulation, we will not conduct a thorough computational study in terms of model sizes and running times. All formulations have been implemented using a mathematical programming language (AIMMS) and solved using CPLEX 12.5. The majority of the models could be solved to optimality on a standard computer in less than ten minutes. The longest computational times occurred for the fault-tolerant



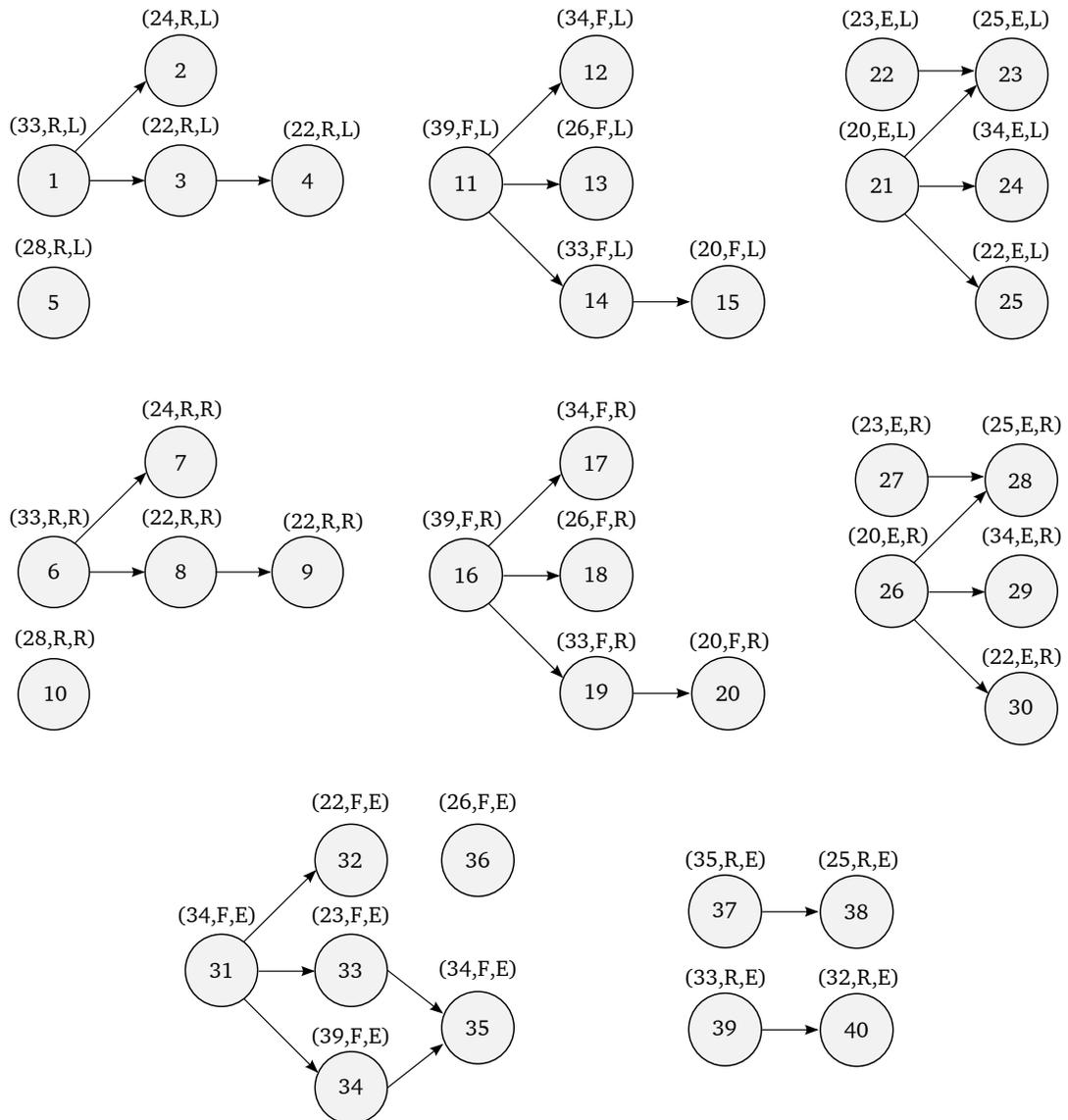
**Figure 5.1:** Layout of the automotive body assembly line.

robotic assembly line balancing problem. However, it should be noted that we only considered a relatively small example. The details of the data used for the numerical study are presented in the next section.

### 5.1.2 Setting and input data

As shown in figure 5.1, the body shop used in our numerical analysis is composed of six stations containing a total of 24 welding robots and one manual repair station at the end of the line. We assume that all robots which are located in the line are prone to failure. Consequently, we have to consider 300 different failure scenarios in the general robot backup formulation as explained above, because preliminary simulations showed that the number of scenarios with three robots failing simultaneously is negligible. The mean time between failure and mean time to repair (*MTBF* and *MTTR*) are assumed to follow an exponential distribution. The exponential distribution is a reasonable assumption for modeling *MTBF* and *MTTR* and frequently used in many simulation experiments. However, it should be noted that in some cases the *MTTR* may not follow the exponential distribution, because in general repair data have more variability than that of the exponential distribution. However, as [Inman \(1999\)](#) found when analyzing actual data from two automotive welding lines, assuming exponentially distributed *MTBF* and *MTTR* does appear valid. Based on their results we can also note that automotive welding lines are characterized by frequent and short robot failures. Consequently, we assume that *MTTR* equals two minutes. Although modern industrial robots provide high

availability, failures occur quite often when considering that the whole system is composed of the robot and the welding gun. Since the available empirical data for the *MTBF* of welding robots is not sufficient, we will use two different values, 200 and 400 minutes of which the former appears to be more valid for automotive welding lines.



**Figure 5.2:** Precedence diagram of the case study.

Figure 5.2 depicts the precedence graph used in our numerical analysis. The

groups of spots are divided into different types, depending on the position and side they have to be assigned to. Each group of spots in the precedence graph is associated with a label  $(t_i, p, d)$  where  $t_i$  is the processing time of task  $i$ ,  $p$  is its position within the station (= rear (R), front (F), or either (E)), and  $d$  (= left (L), right (R), or either (E)) is its operation direction. Due to the symmetry of a typical automotive body shell (cf. figure 2.2) we assume that on both sides of the body the same number of groups of spots is required. Furthermore, we assume that the number of spots on the front of the car has to be higher compared to the rear in order to provide a higher engineering strength. The processing times displayed in the figure are only valid for the initial assignment and robot backup solutions, i.e. only the robotic times are shown. Whenever groups of spots have to be reallocated to the MR station the processing time is three times higher (Kahan et al., 2009).

As stated above, it may not be possible for a particular welding gun to reach to every welding spot location due to its geometry. The capability of a welding gun to perform a group of spots is captured by the WCM. For our experiments we considered three different capability matrices. The WCM was created with regard to the precedence graph, i.e., we also considered the symmetry of the body shell. Consequently, a certain welding gun  $j$  that can reach a group of spots on one side of the body can always reach the corresponding group of spots on the other side of the body. Since there is only one example for a WCM in the literature (cf. Gupta et al. (2012)), we considered three different matrices. The matrices differ with regard to the average number of welding guns that can perform a certain group of spots. The average number of welding guns per group of spots contains three levels (4, 6 and 8). The higher the average number of welding guns per groups of spots is, the more entries of the WCM are equal to one. The WCMs were generated in a consistent manner - as every level of welding guns per groups of spots was built upon the former level. For instance, a welding gun capability matrix with an average number

**Table 5.1:** Parameters used for the numerical analysis.

Parameter	Values		
Average number of welding guns per group of spots	4	6	8
Mean time between failure [minutes]	200	400	

of four welding guns per group of spots was built, to which entries were added up to a level of six and based on this matrix entries were added until reaching a level of eight. The welding gun capability matrices are shown in the appendix B. The experimental factors used in the numerical analysis are summarized in table 5.1. Before presenting the results of the simulation experiments, we will discuss the evaluation criteria used throughout the experiments in the next section.

### **5.1.3 Evaluation criteria**

The evaluation criteria used in our numerical study are the cycle time (1) and the product quality (2). As a surrogate measure for the product quality we collect the number of groups that have to be reallocated to the MR station (in the following referred to as MR groups), because no robotic backup exists. As we discussed in section 2.2.2 one main reason for the implementation of robotic welding lines is that robots are superior to human workers with regard to the accuracy of spot welds. Consequently, a high number of groups of spots that has to be performed in the MR station is associated with lower product quality.

## **5.2 Simulation results**

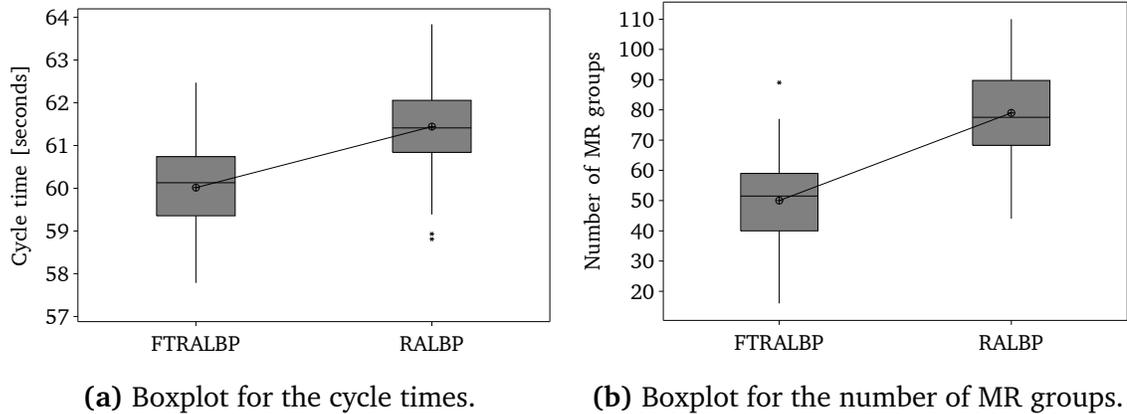
In this section we will report and discuss the results obtained in the simulation study. For each scenario we collected the average cycle time, its standard deviation (among replications) as well as the corresponding half width 95 % confidence level. Additionally, the number of groups reallocated to the MR station and the number of groups reallocated to backup robots were collected in order to define

the quality measure for the line. In particular, the percentage of these numbers with respect to the total number of reallocated groups is reported to compare the different approaches properly.

Every configuration was simulated for each scenario by running 80 replications with a length of two eight-hour shifts of which the first two hours have been used as warm up period, i.e. no statistics were collected during this period. The number of 80 replications was large enough to guarantee relatively tight confidence intervals allowing for strong conclusion as seen below. Since the cycle time for the initial assignment is 55 seconds each run consists of approximately 1,000 cycles. All statistical analyses presented in the following have been done using the statistical software package Minitab in the version 16. In order to compare the two system configurations, we used the two-sample t-test. The two-sample t-test can be used to compare whether two independent groups differ. To apply the two-sample approach both populations have to be normally distributed and have equal variances. While the normality assumption is not critical, the assumption of equal variances is critical especially when the sample sizes differ. Since we used the same number of replications for all our simulation experiments, the runs for the different configurations were independent and the populations follow a normal distribution, we could use the two-sample t-test.

#### *Analysis of cycle time and quality measure for a MTBF of 200 minutes*

In figure 5.3 the boxplots of the cycle time as well as the number of MR groups obtained for an average of four different welding guns per group are illustrated. Boxplots are used to display batches of data. Usually, five values from a set of data are displayed: the upper and lower extremes, the upper and lower quartiles which limit the box and the median. (McGill, Tukey, and Larsen, 1978) As can be seen from the figure, both the cycle time and the number of MR groups are lower for

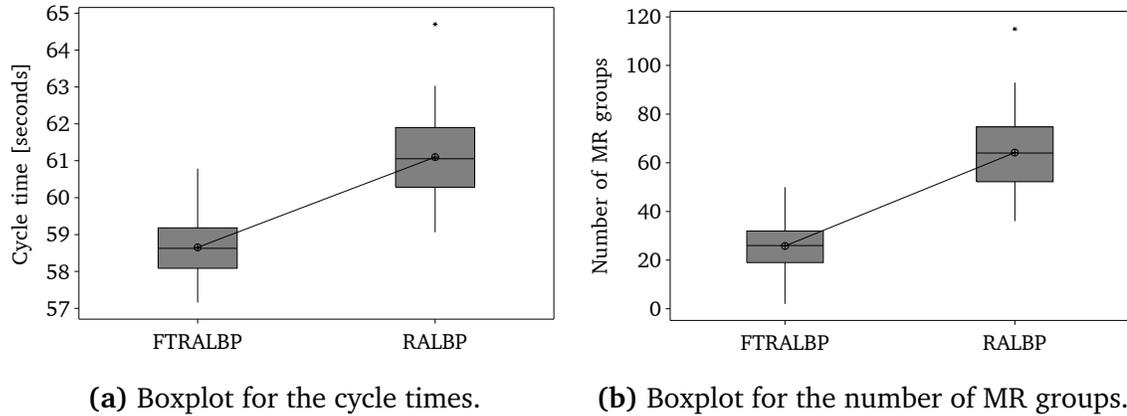


**Figure 5.3:** Boxplots obtained for four welding guns per group of spots.

the FTRALBP. These results are statistically significant with a confidence level of 95 %. The detailed results of the simulation experiment with an average of four welding guns per group of spots and a *MTBF* of 200 minutes are reported in table 5.2. As we can see from the table the FTRALBP provides an average cycle time of 60.01 seconds compared to a cycle time of 61.44 seconds obtained with the RALBP. This is equal to a reduction of the cycle time of 2.33 %. Additionally, only 26.64 % of the groups which require backup are reallocated to the MR station. In contrast, using the RALBP 46.49 % of the groups which require backup have to be assigned to the MR station.

**Table 5.2:** Results of the simulation experiment with four welding guns per group of spots for a *MTBF* of 200 minutes.

	FTRALBP	RALBP
<b>Cycle time</b>		
Average cycle time	60.01	61.44
STD cycle time	0.95	1.09
Cycle time half width (95 %)	0.21	0.24
<b>Failure data</b>		
Groups MR counter	50.00	78.98
Groups backup counter	137.70	90.89
MR groups (%)	26.64	46.49
Backup groups (%)	73.36	53.51



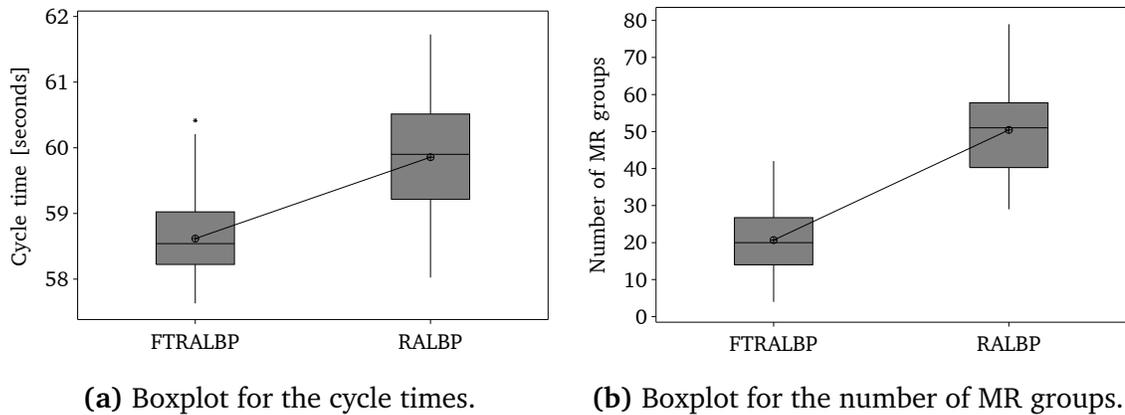
**Figure 5.4:** Boxplots obtained for six welding guns per group of spots and a *MTBF* of 200 minutes.

In figure 5.4 the boxplots of the cycle time as well as the number of MR groups obtained for an average of six different welding guns per group are illustrated. Again, we can see from the boxplots that both the cycle time and the number of MR groups are lower for the FTRALBP. These results are also statistically significant with a confidence level of 95 %. The detailed results of the simulation experiment with six welding guns per group of spots are reported in table 5.3. As we can see from the table our approach provides an average cycle time of 58.65 seconds compared to a cycle time of 61.10 seconds obtained with the RALBP. Hence, for an

**Table 5.3:** Results of the simulation experiment with six welding guns per group of spots for a *MTBF* of 200 minutes.

	FTRALBP	RALBP
Cycle time		
Average cycle time	58.65	61.10
STD cycle time	0.73	1.08
Cycle time half width (95 %)	0.16	0.24
Failure data		
Groups MR counter	25.84	64.20
Groups backup counter	179.78	114.58
MR groups (%)	12.57	35.91
Backup groups (%)	87.43	64.09

average of six welding guns per group of spots, the FTRALBP yields a reduction of the cycle time of 4.01 % compared to the RALBP. Consequently, the difference between the cycle times obtained using the two approaches becomes even bigger compared to the scenario with an average of four welding guns per group of spots. We can make the same observation for the number of groups, which have to be re-allocated. While only 12.57 % of the groups which require backup are reallocated to the MR station for the FTRALBP, 35.91 % of the groups which require backup have to be assigned to the MR station using the RALBP.



**Figure 5.5:** Boxplots obtained for eight welding guns per group of spots and a *MTBF* of 200 minutes.

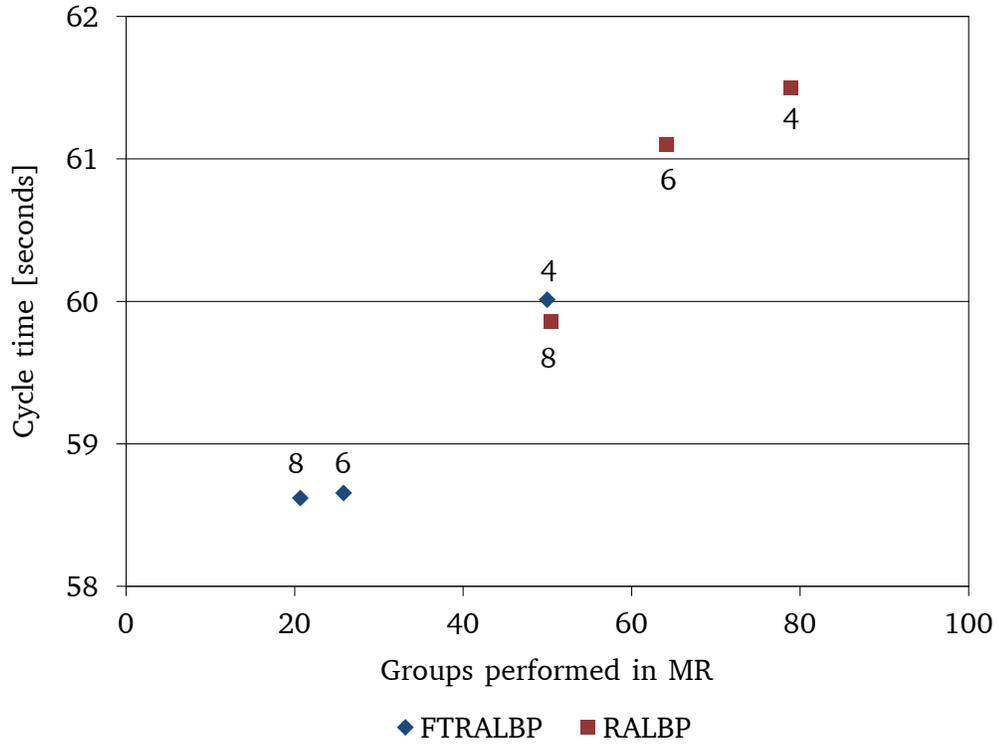
Finally, in figure 5.5 the boxplots of the cycle time as well as the number of MR groups obtained for an average of eight different welding guns per group are illustrated. Again, we can see that both the cycle time and the number of MR groups are lower for the FTRALBP. These results are statistically significant with a confidence level of 95 %. The detailed results of the simulation experiment with eight welding guns per group of spots are reported in table 5.4. As we can see from the table, the FTRALBP provides an average cycle time of 58.62 seconds compared to a cycle time of 59.68 seconds obtained for the RALBP. Hence, our approach performs better. However, the relative difference between the cycle time obtained using the

FTRALBP compared to the RALBP is with 1.78 % smaller as observed for the former two examples with an average of four and six welding guns per group of spots. Again, the FTRALBP performs much better with regard to the number of groups reallocated to the MR station. While only 10.19 % of the groups which require backup are reallocated to the MR station for the FTRALBP, 26.37 % of the groups which require backup have to be assigned to the MR station using the RALBP

**Table 5.4:** Results of the simulation experiment with eight welding guns per group of spots for a *MTBF* of 200 minutes.

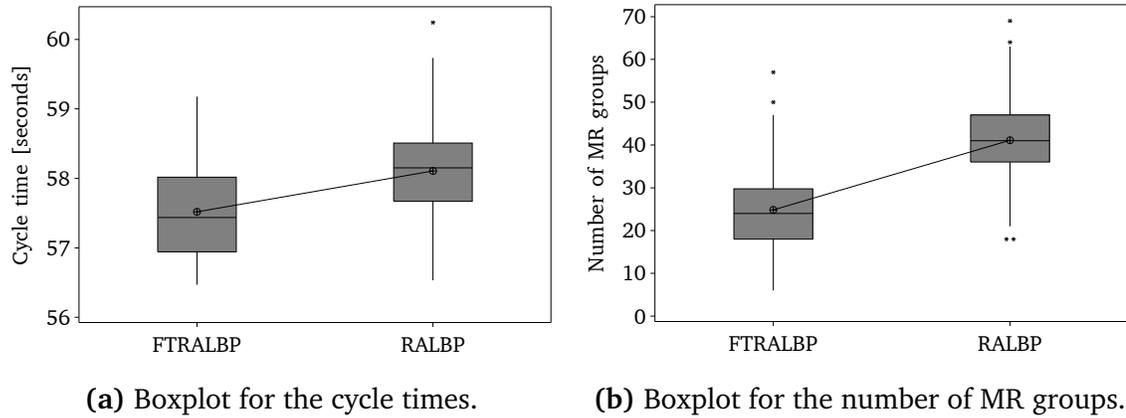
	FTRALBP	RALBP
Cycle time		
Average cycle time	58.62	59.86
STD cycle time	0.55	0.84
Cycle time half width (95 %)	0.12	0.18
Failure data		
Groups MR counter	20.70	50.43
Groups backup counter	182.53	140.80
MR groups (%)	10.19	26.37
Backup groups (%)	89.81	73.63

We already pointed out that the difference between the two approaches depends on the average number of welding guns per group of spots. To allow for better comparisons between the two approaches for the different settings considered, we plotted the average cycle time as well as the average number of MR groups for both approaches and for the three different levels of welding guns per group of spots in figure 5.6. As we can see from figure 5.6, for both approaches the cycle time and the number of MR groups decrease as the average number of welding guns per group of spots increases. These results are quite intuitive, because as the number of welding guns capable of performing a certain group of spots increases, the overall systems' level of redundancy is also expected to increase resulting in an improved cycle time and a smaller number of groups that have to be reallocated



**Figure 5.6:** Cycle time versus quality measure obtained for  $MTBF = 200$  minutes.

to the MR station. Furthermore, we can note that our approach performs better for both the cycle time as well as the number of MR groups for all three levels of the average number of welding guns per group of spots. However, the difference between the two approaches differs with regard to the number of welding guns per group of spots. The best performance of our approach compared to the alternative approach is obtained for six welding guns per group of spots. A further increase in the number of welding guns per group of spots to eight, results in a smaller difference between the two approaches for both cycle time and number of MR groups. This is due to the diminishing return of the number of welding guns per group of spots with regard to the cycle time and the number of MR groups that we can observe for our approach. While an increase in the number of welding guns from four to six results in the major part of improvement of the cycle time and the number of MR groups, a much smaller improvement is associated with a further



**Figure 5.7:** Boxplots obtained for four welding guns per group of spots for a *MTBF* of 400 minutes.

increase in the number of welding guns from six to eight for our approach. On the other hand, for the alternate approach we can observe a smaller improvement for an increase in the number of welding guns from four to six while the major part of improvement is associated with a further increase in the number of welding guns from six to eight.

*Analysis of cycle time and quality measure for a MTBF of 400 minutes*

As we discussed before, we used two different values in our numerical analysis for the value of the *MTBF* in order to analyze whether our approach is still better than the alternative approach when the *MTBF* increases. In the following we will present and discuss the simulation results obtained for a *MTBF* of 400 minutes.

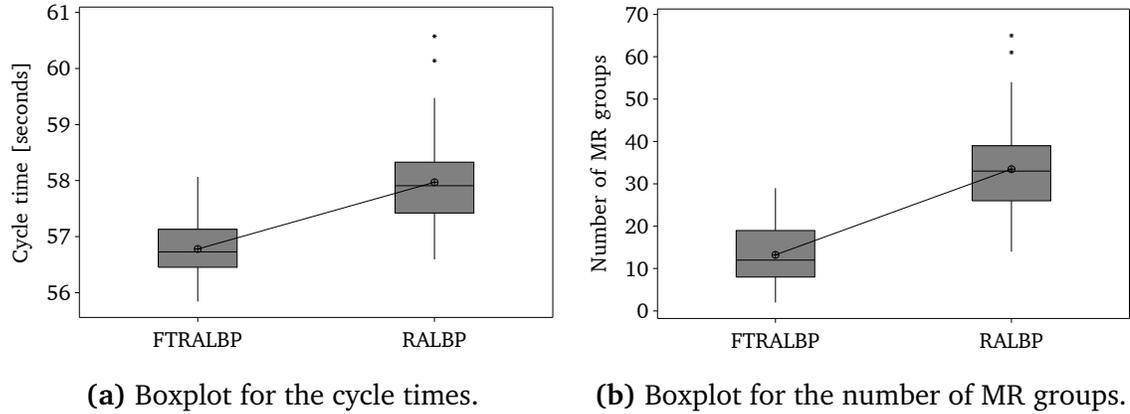
In figure 5.7 the boxplots of the cycle time as well as the number of MR groups obtained for an average of four different welding guns per group are illustrated. Again, we can see from the boxplots that both the cycle time and the number of MR groups are still lower for the FTRALBP. These results are also statistically significant with a confidence level of 95 %. The detailed results of the simulation experiment with four welding guns per group of spots are reported in table 5.5. As we can

**Table 5.5:** Results of the simulation experiment with four welding guns per group of spots for a *MTBF* of 400 minutes.

	FTRALBP	RALBP
Cycle time		
Average cycle time	57.52	58.11
STD cycle time	0.64	0.68
Cycle time half width (95 %)	0.14	0.15
Failure data		
Groups MR counter	24.83	41.10
Groups backup counter	77.90	48.51
MR groups (%)	24.17	45.86
Backup groups (%)	75.83	54.14

see from the table, our approach provides an average cycle time of 57.52 seconds compared to a cycle time of 58.11 seconds obtained with the alternative approach. This equal to a reduction of the cycle time of 1.01 %. Compared to the scenario with a *MTBF* of 200 minutes the relative difference with regard to the cycle time decreases, however, our approach performs better. This is especially true when considering the number of MR groups for the two approaches. While only 24.17 % of the groups that have to be reallocated are assigned to the MR station for our approach, 45.68 % of the groups which require backup have to be assigned to the MR station using the alternative approach. Consequently, our approach performs much better with regard to the quality measure.

In figure 5.8 the boxplots of the cycle time as well as the number of MR groups obtained for an average of six different welding guns per group are illustrated. Again, we can see from the boxplots that both the cycle time and the number of MR groups are lower for our approach. These results are also statistically significant with a confidence level of 95 %. The detailed results of the simulation experiment with six welding guns per group of spots are reported in table 5.6. As we can see from the table, our approach provides an average cycle time of 56.78 seconds compared

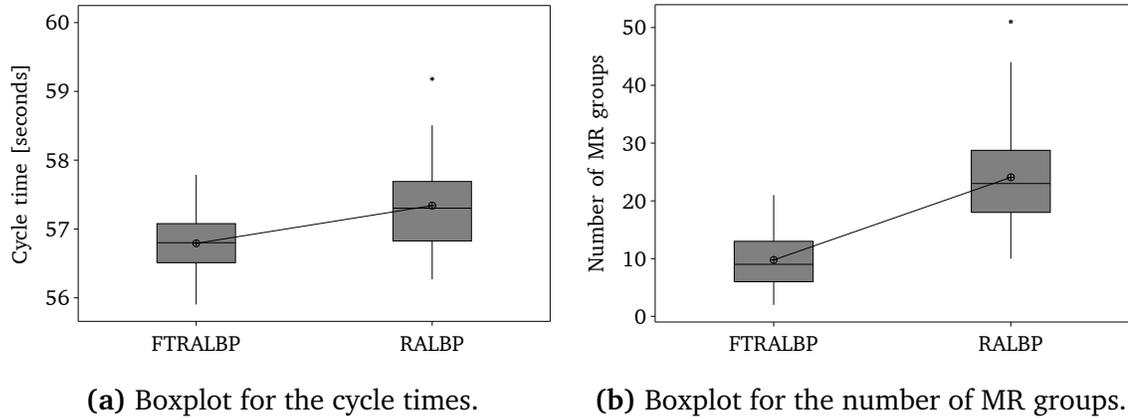


**Figure 5.8:** Boxplots obtained for six welding guns per group of spots for a *MTBF* of 400 minutes.

to a cycle time of 57.97 seconds obtained with the alternate approach. Hence, for an average of six welding guns per group of spots and a *MTBF*, our approach still yields a reduction of the cycle time of 2.01 % compared to the alternative approach. We can make the same observation for the number of groups which have to be re-allocated. While only 12.79 % of the groups which require backup are reallocated to the MR station for our approach, 35.69 % of the groups which require backup have to be assigned to the MR station using the alternative approach.

**Table 5.6:** Results of the simulation experiment with six welding guns per group of spots for a *MTBF* of 400 minutes.

	FTRALBP	RALBP
<b>Cycle time</b>		
Average cycle time	56.78	57.97
STD cycle time	0.47	0.74
Cycle time half width (95 %)	0.10	0.16
<b>Failure data</b>		
Groups MR counter	13.25	33.45
Groups backup counter	90.33	60.28
MR groups (%)	12.79	35.69
Backup groups (%)	87.21	64.31



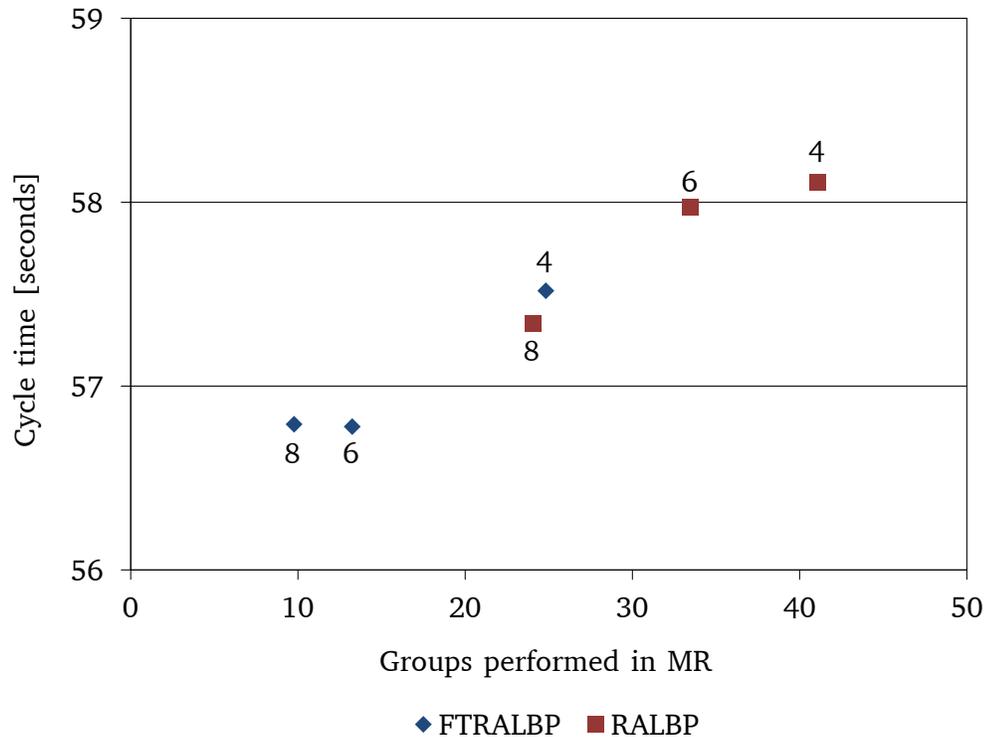
**Figure 5.9:** Boxplots obtained for eight welding guns per group of spots and a *MTBF* of 400 minutes.

Finally, in figure 5.9 the boxplots of the cycle time as well as the number of MR groups obtained for an average of eight different welding guns per group and a *MTBF* of 400 minutes are illustrated. We can still observe that both the cycle time and the number of MR groups are lower for our approach. These results are also statistically significant with a confidence level of 95 %. The detailed results of the simulation experiment with eight welding guns per group of spots are reported in table 5.7 for further analysis. As we can see from the table, our approach provides an average cycle time of 56.79 seconds compared to a cycle time of 57.34 seconds obtained with the alternative approach. Hence, our approach performs better. However, as we have already seen for a *MTBF* of 400 minutes, the relative difference between the cycle time obtained using our approach compared to the alternative approach is with 0.95 % smaller as observed for the former two examples with an average of four and six welding guns per group of spots. Again, our approach perform much better with regard to the number of groups reallocated to the MR station. While only 9.18 % of the groups which require backup are reallocated to the MR station for our approach, 24.15 % of the groups which require backup have to be assigned to the MR station using the alternative approach.

**Table 5.7:** Results of the simulation experiment with eight welding guns per group of spots for a *MTBF* of 400 minutes.

	FTRALBP	RALBP
Cycle time		
Average cycle time	56.79	57.34
STD cycle time	0.43	0.58
Cycle time half width (95 %)	0.09	0.13
Failure data		
Groups MR counter	9.78	24.06
Groups backup counter	96.75	75.56
MR groups (%)	9.18	24.15
Backup groups (%)	90.82	75.85

As we have already done for a *MTBF* of 200 minutes, we will analyze how the differences between the two approaches develop as the average number of welding guns per group of spots increases. To allow for better comparisons between the two approaches for the different settings considered, we plotted the average cycle time as well as the average number of MR groups for both approaches in the same manner as we have done above. The comparison is illustrated in figure 5.10. As we can see from the figure, for both approaches the cycle time and the number of MR groups decrease as the average number of welding guns per group of spots increases. These results are quite intuitive, because as the number of welding guns capable of performing a certain group of spots increases, the overall systems' level of redundancy is also expected to increase resulting in an improved cycle time and a smaller number of groups that have to be reallocated to the MR station. Furthermore, we note that our approach performs better for both the cycle time as well as the number of MR groups for all three levels of the average number of welding guns per group of spots. However, the difference between the two approaches differs with regard to the number of welding guns per group of spots in a very similar manner as we have seen above. The best performance of our



**Figure 5.10:** Cycle time versus quality measure obtained for  $MTBF = 400$  minutes.

approach compared to the alternative approach is again obtained for six welding guns per group of spots. A further increase in the number of welding guns per group of spots to eight results in a smaller difference between the two approaches for both cycle time and number of MR groups. This is due to the diminishing return of the number of welding guns per group of spots with regard to the cycle time and the number of MR groups that we can observe for our approach. While an increase in the number of welding guns from four to six results in the major part of improvement of the cycle time and the number of MR groups, a much smaller improvement is associated with a further increase in the number of welding guns from six to eight for our approach. On the other hand, for the alternate approach we can observe a smaller improvement for an increase in the number of welding guns from four to six while the major part of improvement is associated with a further increase in the number of welding guns from six to eight.

### Results summary of the experimentation

Finally, we present a summary of the results obtained in our simulation study. In table 5.8 the absolute and relative performance of our approach compared to the benchmark with regard to the cycle time is illustrated. For this comparison we used the average values that we collected from the simulation experiments. As seen in table 5.8, our approach performs best for the case of a medium number of welding guns per group of spots (6) for both values of the *MTBF* that have been considered. A further increase in the number of welding guns per group of spots results in a decreased difference between the approaches. When comparing the results obtained for a *MTBF* of 400 minutes to the results obtained for a *MTBF* of 200 minutes, we note that both the absolute and relative performance of our approach are reduced by approximately half.

**Table 5.8:** Absolute and relative performance of our approach compared to the benchmark with regard to the cycle time.

Welding guns per group of spots	<i>MTBF</i> = 200 minutes		<i>MTBF</i> = 400 minutes	
	abs. [sec]	rel. [%]	abs. [sec]	rel. [%]
4	-1.43	-2.33	-0.59	-1.01
6	-2.45	-4.00	-1.19	-2.05
8	-1.24	-2.07	-0.55	-0.95

In table 5.9 the absolute and relative performance of our approach compared to the benchmark with regard to the number of MR groups are reported. Again we used the average values that we collected in the simulation study. As we can see from table 5.9, our approach outperforms the alternative approach by at least 36.69 % for the case of a low number of welding guns per group of spots (4) and a *MTBF* of 200 minutes. This relative difference of our approach compared to the benchmark can rise to 60.39 % for the case of a medium number of welding guns per group of spots (6) and a *MTBF* of 400 minutes. A comparison of the results obtained for

**Table 5.9:** Absolute and relative performance of our approach compared to the benchmark with regard to the number of MR groups.

Welding guns per group of spots	<i>MTBF</i> = 200 minutes		<i>MTBF</i> = 400 minutes	
	abs.	rel. [%]	abs.	rel. [%]
4	-28.98	-36.69	-16.28	-39.60
6	-38.36	-59.75	-20.20	-60.39
8	-29.73	-58.95	-14.29	-59.38

a *MTBF* of 200 minutes to the results obtained for a *MTBF* of 400 minutes reveals that the extent to which our approach outperforms the benchmark is almost stable, yet, even increases slightly as the *MTBF* increases. This is especially interesting, because when comparing the cycle times we observe both decreasing absolute and relative performance of our approach compared to the benchmark for an increasing *MTBF*.

### 5.3 Conclusion

Based on the findings of our numerical study, we will draw the most important conclusions, i.e. we will summarize the benefits of our approach and discuss under which operating conditions it performs particularly well.

Above all, we can state that our approach performs better for all scenarios that have been considered with regard to both evaluation criteria, namely cycle time as well as product quality. When considering the cycle time, our approach performs best for a medium number of welding guns per group of spots. This is true for both values of the *MTBF* that have been considered. However, the relative level of performance decreases as the *MTBF* increases. For a *MTBF* of 200 minutes the reduction of the cycle time is between 2 % and 4 % compared to the benchmark. As the *MTBF* increases the reduction of the cycle time is only between 1 % and 2 %. From this we derive that our approach is particularly well suited for an assem-

bly line which is characterized by short and more frequent failures for a medium number of welding guns per group of spots when considering the cycle time.

With regard to the number of MR groups we get very robust results, i.e. our approach performs much better for both values of the *MTBF*. The reduction of the number of MR groups reaches 60 % compared to the benchmark. For the low number of welding guns per group of spots this reduction is already between 36 % and 39 % for 200 and 400 minutes of the *MTBF*, respectively. As the average number of welding guns per group of spots increases, the reduction is approximately 60 % compared to the benchmark for both values of the *MTBF* that have been considered.

Overall, our approach performs best with regard to both performance measures, i.e. it ensures a low cycle time and high product quality for a medium number of welding guns per group of spots and more frequent failures.

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## Chapter 6

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### Critique of approach and future research

Given the trend towards increasing automation of assembly lines, the requirements for the configuration of such systems change. In particular, breakdowns of machinery become a relevant issue when configuring automated assembly lines, because the breakdown of a single machine or tool can result in the stoppage of the whole line. One industry which has been traditionally highly automated is the automotive industry. The body shop assembly lines are especially characterized by a high level of automation. Spot welds on automotive body shells are performed by up to one hundred and sometimes even more robots, which are subject to failure. Robots' failures result either in line stoppages or manual backup of tasks both leading to decreased productivity. Furthermore, manual backup of tasks tends to impair the products' quality. Therefore, the question has to be answered, of how robots' failures can be considered in the design stage of these systems in order to ensure minimum productivity loss and high product quality in the event of failures.

The modeling approach proposed in this thesis was developed with the intention of providing decision support for this question. The principle idea is to consider not only the systems' cycle time in the initial state where all robots are up - as it is usually done by traditional assembly line balancing approaches - but also take the systems' level of redundancy into account. The contribution of the thesis is twofold. First, we provide a new modeling approach which extends the traditional assembly line balancing approach such that the systems' level of redundancy is

considered. Second, we compare two versions of our approach with a traditional robotic assembly line balancing approach. We can show that our approach yields not only a higher level of redundancy but also smaller average cycle time and utilization of manual repair.

Future research should be directed to the following three main directions. (1) To solve the proposed approach we used the standard solver CPLEX in the version 12.5. This solution approach works fine for problems for which the number of groups of spots as well as stations and robots to be considered is low. If, however, larger problem sizes are considered, the applicability of a standard solver will be limited. Therefore, efficient heuristic solution procedures are required to solve the problem in reasonable computing time. The development of such a heuristic is a promising field for further research. As discussed above, genetic algorithms have been used extensively for assembly line balancing problems. The development of a genetic algorithm for our approach seems to be very promising for two reasons. First, the systems' level of redundancy could be evaluated using a simple encoding procedure, which captures the assignment of groups of spots and welding guns to robots, respectively. Furthermore, genetic algorithms have been used successfully in the field of multi-objective optimization making them suitable for our approach as we optimize cycle time and redundancy level simultaneously. Another advantage of genetic algorithms is that they do not only generate a single solution but instead construct a pareto front, i.e., a set of non-dominated solutions.

(2) A second field for further research arises from the assumption that only one model is assembled on the line. The approach should be generalized such that it supports a mixed-model environment as it is found in the automotive industry. Usually, different models (e.g., sedan, station wagon, coupé) of the same product are assembled on the same line. The models are typically characterized by

different numbers of spot welds required. If the relative frequency of the models is known in advance, one could use a combined precedence graph containing all precedence relationships of the variants to transform the problem into a single model line-balancing problem. In order to account for the different number of weld spots for the models, one could use another form of the redundancy factor, where the groups of spots are weighted by the relative frequency of the model. Although the number of models in the automotive body shop is comparatively low, the consideration of a mixed-model environment would increase the complexity of the problem dramatically.

(3) In a case study we could show that our approach provides the best average performance over all parameter settings considered. However, due to the fact that there is not sufficient empirical data from industrial practice to model all aspects from a real-world body shop line, characteristics of the product structure as well as details concerning the capabilities of different welding guns, we had to make reasonable assumptions. As a result of this, a performance analysis based on a “real-world” setting would be another very interesting field for further research.

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## Chapter 7

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### Summary

Automotive companies employing highly automated assembly lines in their body shops struggle with the challenge of robots' failures which result either in stoppages of the line or in manual backup of operations. These phenomena tend to impair the systems' productivity as well as the products' quality. Therefore, the consideration of robot failures in the design stage of an assembly line considerably gains in importance. In this thesis we develop an approach to configure a robotic assembly line such that it is more robust against robots' failures. The principle idea is that in the event of a robot failure working robots perform the tasks of failed robots. The throughput loss in these backup situations mainly depends on the systems' level of redundancy, i.e. the higher the systems' level of redundancy the more robust it is against robot failures. Consequently, we develop an approach to design the line such that the systems' level of redundancy is maximized.

Our study is based on a detailed discussion of the processes and technology used in automotive body shop systems. After briefly describing all stages of an automotive plant, the body assembly process is discussed in detail. We describe the equipment which is used in the different assembly operations, which are required to assemble the body shell of an automobile. Based on these information about automotive body shop systems we can later derive technological restrictions, which have to be considered in our approach for fault-tolerant design of body assembly lines.

Then we move on to give an overview about existing approaches for the configura-

tion of assembly lines. After introducing the basic terms related to assembly lines and simple models for the configuration we focus on examining generalized assembly line balancing problems for highly automated lines as well as lines producing large products such as automobiles. We provide a critical assessment of existing approaches with regard to their suitability for the purpose of fault-tolerant flow-line design. Since none of the existing approaches considers robots' failures at the design stage of assembly lines, we propose an approach for fault-tolerant design of automotive body assembly lines.

We provide a numerical analysis in which we compare the performance of our approach with that of a traditional robotic assembly line balancing robot. The results of our study are presented and discussed in detail. In order to evaluate our approach we use performance measures for the average cycle time and the product quality. In all settings considered we find that our approach performs better or at least as good as the benchmark.

## Appendix

### Appendix A: General robot backup (GRB) formulation from Kahan et al. (2009)

In the following we present the formulation from Kahan et al. (2009) which has been used extensively in our numerical study. For the major part we use the original notation from the authors. However, at some points we make minor changes in order to ensure that the notation of their formulation is in accordance with our formulation.

*Sets and parameters:*

$I$  = set of total group of spots

$I^W$  = set of total groups of spots assigned to working robots  $I^W \subseteq I$

$I^F$  = set of total groups of spots assigned to failed robots  $I^F = I/I^W$

$R$  = set of all the robots located in the assembly line

$R^W$  = set of working robots  $R^W \subseteq R$

$R^F$  = set of failed robots  $R^F = R/R^W$

$R_{Max}$  = maximum number of backup robots

$t_i$  = performance time of of group of spots  $i$  (including setup)

$IP_i^W$  = set of immediate predecessors of group  $i$  assigned to working robots

$IS_i^W$  = set of immediate successors of group  $i$  assigned to working robots

$IP_i^F$  = set of immediate predecessors of group  $i$  assigned to failed robots

$IS_i^F$  = set of immediate successors of group  $i$  assigned to failed robots

*Matrices:*

Two matrices describe the current and the potential work allocation in the system. The former is given by the initial matrix ( $IM$ ) and the latter by the robot capability matrix ( $RCM$ ). Both matrices are the result of our approach where the  $IM$  is given by the allocation of groups of spots to robots and the  $RCM$  is defined by the allocation of welding guns to robots.

$$IM_{ir} = \begin{cases} 1, & \text{if group of spots } i \text{ is performed by robot } r \text{ in the initial state} \\ 0, & \text{otherwise.} \end{cases}$$

$$RCM_{ir} = \begin{cases} 1, & \text{if group of spots } i \text{ can be performed by robot } r \\ 0, & \text{otherwise.} \end{cases}$$

*Decision variables:*

Three decision variables are used in the formulation. The recovery matrix,  $rm_{ir}$ , indicates whether a group of spots  $i$  is reallocated to robot  $r$  after failure. As in our formulation, the cycle time is denoted by the variable  $C$  here as well. Finally,  $z_r$  indicates whether a certain robot  $r$  is a backup robot.

$$C = \text{Cycle time}$$

$$rm_{ir} = \begin{cases} 1, & \text{if group of spots } i \text{ is performed by robot } r \text{ in the initial state} \\ 0, & \text{otherwise.} \end{cases}$$

$$z_r = \begin{cases} 1, & \text{if robot } r \text{ is a backup robot} \\ 0, & \text{otherwise.} \end{cases}$$

Model GRB:

$$\text{Minimize } C \tag{A.1}$$

subject to:

$$\sum_{i \in I^W} t_i \cdot IM_{ir} + \sum_{i \in I^F} t_i \cdot rm_{ir} \leq C \quad \forall r \in R^W \tag{A.2}$$

$$\sum_{r \in R^W} rm_{ir} = 1 \quad \forall i \in I^F \tag{A.3}$$

$$z_r \geq rm_{ir} \quad \forall i \in I^F, \forall r \in R^W \tag{A.4}$$

$$rm_{ir} \leq RCM_{ir} \quad \forall i \in I^F, \forall r \in R^W \tag{A.5}$$

$$\sum_{k \in R^W} k \cdot IM_{hk} \leq \sum_{l \in R^W} l \cdot rm_{il} \quad \forall i \in I^F, \forall h \in IP_i^W \tag{A.6}$$

$$\sum_{k \in R^W} k \cdot rm_{ik} \leq \sum_{l \in R^W} l \cdot IM_{gl} \quad \forall i \in I^F, \forall g \in IS_i^W \tag{A.7}$$

$$\sum_{k \in R^W} k \cdot rm_{hk} \leq \sum_{l \in R^W} l \cdot rm_{il} \quad \forall i \in I^F, \forall h \in IP_i^F \tag{A.8}$$

$$\sum_{k \in R^W} k \cdot rm_{ik} \leq \sum_{l \in R^W} l \cdot rm_{hl} \quad \forall i \in I^F, \forall h \in IS_i^F \tag{A.9}$$

$$\sum_{r \in R^W} z_r \leq R_{Max} \tag{A.10}$$

$$rm_{ir} \in 0, 1 \quad \forall i \in I^F, \forall r \in R^W \tag{A.11}$$

$$z_r \in 0, 1 \quad \forall r \in R \tag{A.12}$$

$$C \geq 0 \tag{A.13}$$

The objective function (A.1) minimizes the systems' cycle time. The cycle time constraint set (A.2) enforces the cycle time to be larger than or equal to the processing time of the robot with the highest load. This equation consists of two parts. The first part captures the constant assembly time, namely, the initial assembly time of the robot prior to any robots' failure. The second part contains the additional assembly time added to a working robot due to other robots' failures. According to constraint set (A.3), each group of spots previously done by the failing robot(s) will be backed up by some working robot. Constraint (A.4) forces the  $z_r$  variables to be equal to 1 if robot  $r$  is a backup robot. Whether a certain robot  $r$  is suitable to serve as a backup robot is checked by constraint set (A.5).

Constraint sets (A.6) - (A.9) are precedence constraints which ensure that the new assignment of the failed groups will still satisfy the technological precedence relationships. Constraint sets (A.6) and (A.8) assure that a failed group  $i$  will be performed after the completion of each of its immediate predecessor,  $h$ , as group  $h$  belongs to a working robot in the former and to a failed robot in the latter. Constraint sets (A.7) and (A.9) enforce the failed task  $i$  to be completed before starting each of its immediate successors,  $g$ , as group  $g$  belong to a working robot in the former and to a failed robot in the latter.

Constraint set (A.10) is optional and enables to limit the number of backup robots. Note that for our numerical study the number of backup robots has not been limited. Constraint sets (A.11) and (A.12) define the decision variables  $rm_{i,r}$  and  $z_r$  as binary variables. Finally, constraint set (A.13) ensures non-negativity of the cycle time.

## Appendix B: Welding gun capability matrices used for the numerical analysis

**B.1:** Welding gun capability matrix with four welding guns per group of spots.

Group of spots $i$	Welding gun $j$									
	1	2	3	4	5	6	7	8	9	10
1	1	1	0	1	0	1	0	0	1	0
2	0	0	0	0	0	0	1	1	0	1
3	1	0	1	1	1	0	0	0	0	1
4	0	0	0	0	0	1	1	0	1	0
5	0	1	0	0	1	0	0	1	0	0
6	1	1	0	1	0	1	0	0	1	0
7	0	0	0	0	0	0	1	1	0	1
8	1	0	1	1	1	0	0	0	0	1
9	0	0	0	0	0	1	1	0	1	0
10	0	1	0	0	1	0	0	1	0	0
11	0	0	1	0	1	0	0	1	0	1
12	1	1	0	1	0	1	0	0	1	0
13	0	0	0	0	1	0	1	1	1	0
14	0	1	1	1	0	1	0	0	0	0
15	1	1	0	0	1	0	0	0	0	1
16	0	0	1	0	1	0	0	1	0	1
17	1	1	0	1	0	1	0	0	1	0
18	0	0	0	0	1	0	1	1	1	0
19	0	1	1	1	0	1	0	0	0	0
20	1	1	0	0	1	0	0	0	0	1
21	1	0	0	0	0	0	0	0	1	0
22	0	0	1	0	1	1	0	1	0	1
23	0	1	1	0	0	0	1	0	1	0
24	0	0	0	1	1	1	0	1	0	0
25	1	1	0	1	0	0	1	0	0	1
26	1	0	0	0	0	0	0	0	1	0
27	0	0	1	0	1	1	0	1	0	1
28	0	1	1	0	0	0	1	0	1	0
29	0	0	0	1	1	1	0	1	0	0
30	1	1	0	1	0	0	1	0	0	1
31	1	0	0	0	1	0	0	1	0	1
32	0	0	1	0	0	0	1	0	1	0
33	0	1	0	1	0	1	0	1	0	1
34	1	1	1	0	1	0	0	0	1	0
35	0	0	1	0	0	1	1	1	0	0
36	1	1	0	0	1	0	0	0	1	0
37	0	0	1	0	1	0	0	0	1	0
38	0	1	0	0	0	0	1	1	0	1
39	1	0	1	1	0	1	0	0	0	0
40	0	1	0	0	1	0	1	0	1	0

**B.2:** Welding gun capability matrix with six welding guns per group of spots.

Group of spots $i$	Welding gun $j$									
	1	2	3	4	5	6	7	8	9	10
1	1	1	0	1	0	1	0	1	1	0
2	1	0	0	1	0	0	1	1	0	1
3	1	1	1	1	1	1	0	0	0	1
4	1	0	0	0	0	1	1	0	1	1
5	0	1	0	0	1	0	1	1	1	1
6	1	1	0	1	0	1	0	1	1	0
7	1	0	0	1	0	0	1	1	0	1
8	1	1	1	1	1	1	0	0	0	1
9	1	0	0	0	0	1	1	0	1	1
10	0	1	0	0	1	0	1	1	1	1
11	1	0	1	1	1	1	0	1	0	1
12	1	1	0	1	0	1	1	1	1	1
13	0	0	0	0	1	0	1	1	1	1
14	0	1	1	1	0	1	0	0	1	0
15	1	1	0	0	1	1	0	0	1	1
16	1	0	1	1	1	1	0	1	0	1
17	1	1	0	1	0	1	1	1	1	1
18	0	0	0	0	1	0	1	1	1	1
19	0	1	1	1	0	1	0	0	1	0
20	1	1	0	0	1	1	0	0	1	1
21	1	1	0	0	1	1	0	0	1	1
22	0	1	1	0	1	1	1	1	1	1
23	1	1	1	0	0	0	1	0	1	0
24	0	0	0	1	1	1	0	1	0	1
25	1	1	0	1	0	1	1	0	1	1
26	1	1	0	0	1	1	0	0	1	1
27	0	1	1	0	1	1	1	1	1	1
28	1	1	1	0	0	0	1	0	1	0
29	0	0	0	1	1	1	0	1	0	1
30	1	1	0	1	0	1	1	0	1	1
31	1	0	1	1	1	0	0	1	1	1
32	0	0	1	1	0	0	1	0	1	1
33	0	1	0	1	0	1	0	1	0	1
34	1	1	1	0	1	1	0	0	1	1
35	1	0	1	0	0	1	1	1	0	0
36	1	1	0	1	1	0	1	0	1	1
37	0	1	1	0	1	0	1	0	1	1
38	0	1	1	1	0	0	1	1	0	1
39	1	0	1	1	0	1	0	1	0	0
40	0	1	1	0	1	0	1	0	1	0

**B.3: Welding gun capability matrix with eight welding guns per group of spots.**

Group of spots $i$	Welding gun $j$									
	1	2	3	4	5	6	7	8	9	10
1	1	1	0	1	1	1	1	1	1	0
2	1	1	1	1	0	0	1	1	0	1
3	1	1	1	1	1	1	0	0	1	1
4	1	0	1	0	1	1	1	1	1	1
5	0	1	1	1	1	1	1	1	1	1
6	1	1	0	1	1	1	1	1	1	0
7	1	1	1	1	0	0	1	1	0	1
8	1	1	1	1	1	1	0	0	1	1
9	1	0	1	0	1	1	1	1	1	1
10	0	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	0	1	0	1
12	1	1	1	1	0	1	1	1	1	1
13	0	0	1	1	1	0	1	1	1	1
14	1	1	1	1	1	1	1	0	1	0
15	1	1	0	0	1	1	1	1	1	1
16	1	1	1	1	1	1	0	1	0	1
17	1	1	1	1	0	1	1	1	1	1
18	0	0	1	1	1	0	1	1	1	1
19	1	1	1	1	1	1	1	0	1	0
20	1	1	0	0	1	1	1	1	1	1
21	1	1	0	1	1	1	1	0	1	1
22	1	1	1	1	1	1	1	1	1	1
23	1	1	1	0	1	0	1	1	1	0
24	0	0	1	1	1	1	0	1	0	1
25	1	1	1	1	0	1	1	1	1	1
26	1	1	0	1	1	1	1	0	1	1
27	1	1	1	1	1	1	1	1	1	1
28	1	1	1	0	1	0	1	1	1	0
29	0	0	1	1	1	1	0	1	0	1
30	1	1	1	1	0	1	1	1	1	1
31	1	1	1	1	1	0	0	1	1	1
32	1	0	1	1	0	1	1	1	1	1
33	0	1	0	1	1	1	1	1	0	1
34	1	1	1	0	1	1	1	0	1	1
35	1	1	1	1	1	1	1	1	1	0
36	1	1	1	1	1	0	1	1	1	1
37	1	1	1	0	1	1	1	0	1	1
38	0	1	1	1	0	1	1	1	1	1
39	1	0	1	1	1	1	0	1	0	1
40	1	1	1	1	1	0	1	1	1	0

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