University of West Bohemia
FACULTY OF MECHANICAL ENGINEERING

Study program: N0715A270012 Industrial Engineering and Management
Study field: N0715A270012S00

MASTER'S THESIS

Simulation and modelling in Advanced production planning system

Author: **Bc. Martin Valenta**

Supervisor: **Ing. Marek Bureš, Ph.D.**

Academic year 2020/2021

ZÁPADOČESKÁ UNIVERZITA V PLZNI
Fakulta strojní
Akademický rok: 2020/2021

ZADÁNÍ DIPLOMOVÉ PRÁCE
(projektu, uměleckého díla, uměleckého výkonu)

Jméno a příjmení:	**Bc. Martin VALENTA**
Osobní číslo:	**S19N0079K**
Studijní program:	**N0715A270012 Průmyslové inženýrství a management**
Studijní obor:	**Průmyslové inženýrství a management**
Téma práce:	**Simulace a modelování v systému pro pokročilé plánování výroby**
Zadávající katedra:	**Katedra průmyslového inženýrství a managementu**

Zásady pro vypracování

1. Introduction to Advanced Planning and Scheduling (APS)
2. APS application characteristics
3. Modelling of input data sets for APS
4. Model simulation for a data sample
5. Application of model simulation solutions to a productive system
6. Evaluation of the simulation results
7. Conclusion

Rozsah diplomové práce:	**50 – 70 stran**
Rozsah grafických prací:	**0 výkresů**
Forma zpracování diplomové práce:	**tištěná**
Jazyk zpracování:	**Angličtina**

Seznam doporučené literatury:

1. MAUERGAUZ, Yuri. *Advanced Planning and Scheduling in Manufacturing and Supply Chains.* Berlin: Springer International Publishing, 2016. ISBN 978-3-319-80161-2.
2. KIRAN, D.R. *Production Planning and Control: A Comprehensive Approach.* Amsterdam: Elsevier Books, 2019. ISBN 978-0-12-818364-9.
3. KEŘKOVSKÝ, Miroslav, VALSA, Ondřej. *Moderní přístupy k řízení výroby.* 3rd ed. Praha: C. H. Beck, 2012. ISBN 978-80-7179-319-9.

Vedoucí diplomové práce:	**Ing. Marek Bureš, Ph.D.** Regionální technologický institut
Konzultant diplomové práce:	**Ing. Pavel Boháč** AIMTEC a. s., Plzeň
Datum zadání diplomové práce:	**21. září 2020**
Termín odevzdání diplomové práce:	**28. května 2021**

L.S.

Doc. Ing. Milan Edl, Ph.D. děkan	**Doc. Ing. Michal Šimon, Ph.D.** vedoucí katedry

V Plzni dne 21. září 2020

Prohlášení o autorství

Předkládám tímto k posouzení a obhajobě diplomovou práci zpracovanou na závěr studia na Fakultě strojní Západočeské univerzity v Plzni.
Prohlašuji, že jsem tuto diplomovou práci vypracoval samostatně, s použitím odborné literatury a pramenů uvedených v seznamu, který je součástí této diplomové práce.

V Plzni dne: …………………….   . . . .
podpis autora

Poděkování

Rád bych poděkoval svému vedoucímu diplomové práce Ing. Marku Burešovi, Ph.D. za odborné vedení a cenné rady. Dále bych chtěl poděkovat společnosti Aimtec a.s. za poskytnutí licence APS systému Asprova a především svému konzultantu Ing. Pavlu Boháčovi, který mne ochotně vedl v průběhu celého roku.

ANOTAČNÍ LIST DIPLOMOVÉ PRÁCE

AUTOR	**Příjmení** Valenta	**Jméno** Martin
STUDIJNÍ OBOR	N0715A270012S00 „Průmyslové inženýrství a management“	
VEDOUCÍ PRÁCE	**Příjmení (včetně titulů)** Ing. Bureš, Ph.D.	**Jméno** Marek
PRACOVIŠTĚ	ZČU - FST - KPV	
DRUH PRÁCE	**DIPLOMOVÁ**	~~**BAKALÁŘSKÁ**~~ / **Nehodící se škrtněte**
NÁZEV PRÁCE	Simulace a modelování v systému pro pokročilé plánování výroby	

FAKULTA	strojní	**KATEDRA**	KPV	**ROK ODEVZD.**	2021

POČET STRAN (A4 a ekvivalentů A4)

CELKEM	75	**TEXTOVÁ ČÁST**	65	**GRAFICKÁ ČÁST**	10

STRUČNÝ POPIS (MAX 10 ŘÁDEK) **ZAMĚŘENÍ, TÉMA, CÍL POZNATKY A PŘÍNOSY**	Diplomová práce se zabývá systémy pro pokročilé plánování výroby. První část práce pojednává o vývoji plánovacích softwarů a o jejich využití. Zahrnuje představení problematiky klientova zadání a spolupracujících subjektů. V druhé části je provedeno navržení algoritmu pro plánování SMT linek s dvojím tokem, jeho testování a následná evaluace výsledků. Celou práci pak zakončuje ekonomické hodnocení projektu.
KLÍČOVÁ SLOVA **ZPRAVIDLA JEDNOSLOVNÉ POJMY, KTERÉ VYSTIHUJÍ PODSTATU PRÁCE**	pokročilé plánování výroby, APS systém, plošný spoj, povrchová montáž, linka s dvojím tokem, Asprova APS, průmyslové inženýrství

SUMMARY OF DIPLOMA SHEET

AUTHOR	**Surname** Valenta	**Name** Martin
FIELD OF STUDY	N0715A270012S00 „Industrial Engineering and Management“	
SUPERVISOR	**Surname (Inclusive of Degrees)** Ing. Bureš, Ph.D.	**Name** Marek
INSTITUTION	ZČU - FST - KPV	

TYPE OF WORK	**DIPLOMA**	~~**BACHELOR**~~	**Delete when not applicable**
TITLE OF THE WORK	Simulation and modelling in Advanced production planning system		

FACULTY	Mechanical Engineering	**DEPARTMENT**	Industrial Engineering and Management	**SUBMITTED IN**	2021

NUMBER OF PAGES (A4 and eq. A4)

TOTALLY	75	**TEXT PART**	65	**GRAPHICAL PART**	10

BRIEF DESCRIPTION **TOPIC, GOAL, RESULTS AND CONTRIBUTIONS**	The Master´s thesis discuss advanced planning and scheduling systems. The first part analyzes the development of the planning software and its use. It contains the introduction of the involved subjects and the introduction to the client assignment. The second part contains developing the scheduling algorithm for the dual-rail SMT line, testing, and evaluating the results. At the end of the thesis is the economic evaluation of the whole project is executed.
KEY WORDS	advanced planning and scheduling system, APS system, printed circuit board, surface mount technology, dual-rail line, Asprova APS, industrial engineering

Table of contents

List of figures

List of tables

List of Abbreviations

APS	Advanced Planning and Scheduling
MRP	Material Requirements Planning
ERP	Enterprise Resource Planning
SMT	Surface Mount Technology
BOM	Bill of Materials
MPS	Master Production Schedule
IR	Inventory Records
PO	Purchase Orders
MP	Material Plan
WO	Work Orders
MRP II	Manufacturing Resource Planning
JIT	Just in Time
CRM	Customer relationship management
HR	Human resources
PLN	Planning department
PRD	Production
PUR	Purchase department
ES	End - Start
SS	Start - Start
SSEE	Start - Start - End - End
EES	End Every - Start
ESE	End - Start Every
MES	Manufacturing Execution System
SED	Schedule Editor

MS	Manufacturing Scheduler
NLS	Network License Server
DS	Data Server
PCB	Printed circuit board
SMD	Surface mount device
QTY	Quantity
FIFO	First in, First out
ROI	Return on investment
PP	Payback period

Introduction

Advanced Planning and Scheduling (APS) as a successor of Material Requirements Planning (MRP) and the supplement for Enterprise Resource Planning (ERP) is one of the planning tools for smooth manufacturing. Thanks to this system, production planning departments can easily make a manufacturing and logistic schedule according to clients' orders, stock or delivery status, and production capacity.

The high requirements for flexibility and manufacturing effectiveness also require advanced software for managing the manufacturing processes. The following thesis describes the basics of the APS system and its predecessors with pros and cons. This background of the whole planning and scheduling concept is fundamental for understanding why the simpler planning and scheduling methods are not satisfactory. This thesis describes the development of planning and scheduling systems in a nutshell.

After this theoretic introduction, the simple model of the APS simulation in Asprova software follows. However, before the simulation of any model, this thesis will determine the correct data format according to available software (in this case, Asprova APS software) and also according to the client's requirements.

For the thesis's purpose, the client provided information regarding the current situation: constraints, manufacturing data, and basic requirements. Based on this data, the analysis and the development of a simple model simulation were created. It will collect the model simulation data and use its results for our client's functional manufacturing system setup. This thesis's final output will be the model of the real client's function system in APS Asprova software for the company uses.

Into this research are involved the client company, and the co-researcher company AIMTEC a. s. as a consultant and intermediary (thesis body includes a detailed description of both companies). The mentioned client's functional manufacturing system is an SMT line, which this thesis will optimize according to the client's request in the Asprova APS system.

Master´s Thesis goals

- Introduction of the APS systems in the context of planning and scheduling software evolution.
- Explanation of how the APS works
- Definition of the client's input data to the appropriate form for this research.
- Development of the model of a simple manufacturing system and analyze the results.
- Application of these results for the client's functional manufacturing system.

1 Introduction to Advanced Planning and Scheduling

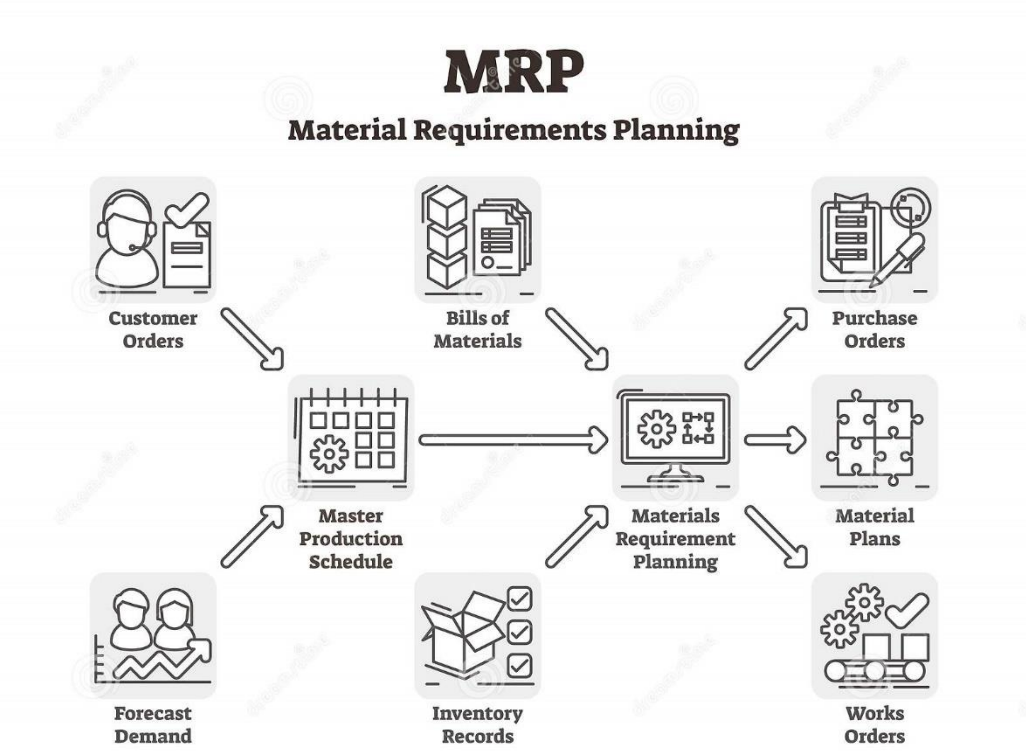
1.1 Material Requirements Planning (MRP)

In 1975 the Czech immigrant in the USA, Joseph Orlicky, published his book named Material requirements planning: the new way of life in production and inventory management. This book presented possible ways how to manage the manufacturing inventory using computer technology. Even nowadays, in 2020, he is considered a spiritual father of all planning and scheduling systems, and as he said, "Never forecast what you can calculate," correctly describing the whole complex of manufacturing planning activities.[1]

To effectively manufacture, it is necessary to clarify What, When, How much, and Where the materials are needed. If there is a shortage of material, wasting by waiting will happen, and the manufacturing order will be unfulfilled. On the other hand, if there are more materials than needed, the company will also waste, but now by cost for storage and tied money in the unnecessary material. Joseph Orlicky solved this logistic problem using the mentioned MRP system on those days' new computer technology.[1]

1.1.1 MRP inputs

Material Requirements Planning is a system that includes three main basic subjects, namely the Bills of Materials (BOM), Inventory Records (IR), and the Master Production Schedule (MPS). The last mentioned is developed based on the Customers Orders and Forcast Demand. For a clear understanding of these MRP system subparts, the explanation follows. Based on this system subparts, the MRP can make the Purchase Orders, Material plans, and the Works Orders (see Picture 1-1). [1]



Picture 1-1: Material Requirements Planning [3]

- **Master Production Schedule**

In order to keep manufacturing organized and smooth, it is necessary to make a Master Production Schedule. MPS collects the customer's orders and the Forecast Demand, calculated according to its orders history. It means that to cover all future customer's manufacturing orders, the MPS uses the forecast to plan with the not yet existing customer's orders. That is one of the signs which characterize the PUSH type of inventory control. The real manufacturing is no hundred percent PUSH or PULL system because the pure PUSH system means that there will be no consideration of current customer orders. On the other hand, the pure PULL system means planting a tree in order to make the wooden table. There are also other definitions of these two systems. For example, PUSH and PULL systems are not about the material flow, which is pushing or pulling, but about the limits of work in progress. However, this master thesis considers MRP as a system where the PUSH type of inventory control prevails over the PULL type (Further, in this thesis, the MRP system is considered a PUSH type). Thus formulated, MPS enters the MRP system together with the BOM and IR. [1][2]

- **Bills of Materials**

The second primary source of the MRP system is the Bill of Materials (BOM). These Bills include each finished product, its assemblies, subassemblies, purchased parts, manufactured parts, and the needed raw materials. After this decomposition, the planner and the system have a table of the material demand. This demand must be covered by the on-hand inventory or by the deliveries from the company's suppliers. [4]

As was mentioned in the previous paragraph, the demand has to be covered in two possible ways. Firstly by the company's on-hand stock or by the deliveries from its suppliers. In both ways, the system has to calculate how many parts, subparts, and materials the manufacture needs to satisfy the customer order. Thus, it is useful to divide the demands into two categories: Independent demands and Dependent demands. Independent demand (also called parent) is a demand for the finished product. This parent demand gathers subassemblies called Dependent demands. It leads to determine order quantities for each customer order—the whole process is described later in this chapter. [5]

- **Inventory Records**

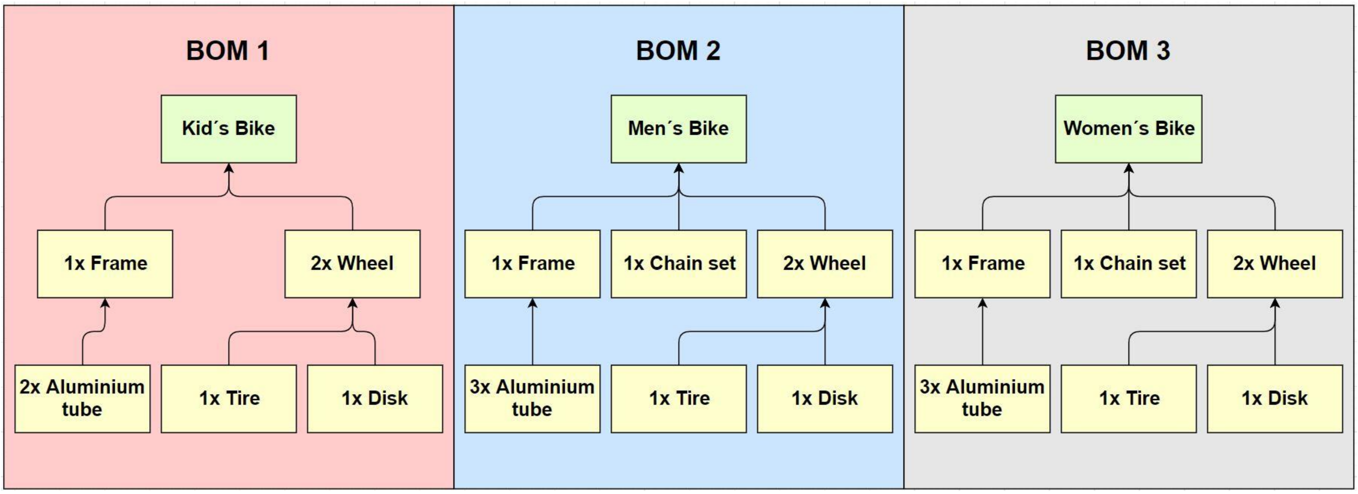
The last primary source that enters into the MRP system is Inventory records. During order processing, it is necessary to know the company's stocks (IR provides the expected amount of on-hand stock or items to be delivered). Suppose the stock on hand cannot cover manufacturing dependent demand. In that case, the purchasing department must consider the delivery time and place an order (IR also contains such information as a Vendor name, Vendor number, lot size, or lead-time). It is a continuous process between the company and the suppliers when the supplies and the company's manufacturing must be consistent. [5]

It is appropriate to state an example for a better understanding of this concept. Suppose the middle-sized manufacturing company produces simple bikes with customers' orders, such as fifty kid's bikes, one hundred men's bikes, and forty women's bikes in the coming quarter. According to this order quantity and the quantity for the last x quarters is determined the forecast for the next two quarters. If this entire order quantity and forecast are summarized, the MPS is complete, and the MRP has the first primary source set up.

The next required ones are BOMs of finished products that are graphically viewed in the picture (see Picture 1-2). This case is a prerequisite for three BOMs: kid's bike (BOM 1), man's bike (BOM 2), and a woman's bike (BOM 3). In this model case is Independent demand the bike (green cells); Dependent demands the bike frame, wheel, hooker, chainset, aluminum tube, Tire, and Disk (yellow cells). The last primary source is IR, as was mentioned.

BOM	BOM 1	BOM 2	BOM 3	SUM
QTY	50	100	40	190
Alluminum Tube	2*1*50 = 100	3*1*100 = 300	3*1*40 = 120	520
Tire	1*2*50 = 100	1*2*50 = 100	1*2*50 = 100	300
Disk	1*2*50 = 100	1*2*50 = 100	1*2*50 = 100	300
Chain set	0	1*100 = 100	1*100 = 100	200

Table 1-1: MRP calculation



Picture 1-2: Independent/Dependent demands

Thanks to BOM, the system exactly knows about the needed components and its quantity. In this case, 190 bikes' manufacturing in this quarter requires 520m of aluminum tube, 300pc of the Tire, 300pc of Disk, and 200pc Chains set. It is connected to MPS because, according to the master schedule, the system determines the exact time of taking components which manufacturing needs. From IR, the data is drawn by the system to determine the on-hand stock's status. It leads to the making of the forecast for new orders from the company's suppliers. If all input data in the right form are uploaded, the MRP system has all the required data to determine the required components and the time of need of these components in the right quantity. [1]

1.1.2 MRP outputs

The output of MRP processing is usually dividing into three main categories: Purchase Orders (PO), Material Plan (MP), and Work Orders (WO).

- **Purchase Orders**

Purchase Orders list from the MRP system is a schedule for the purchasing (from the company's suppliers). Based on BOM, MPS, and IR, this output provides due dates of delivery according to MPS with the required quantity to meet the BOM with considering of IR.

- **Material Plan**

List with the detailed description of finished products with its parts and subparts with QTY and dates.

- **Work Orders**

Work Orders list determines the work, which leads to the final product. It includes all necessary materials, milestone dates, and responsible persons or departments.

Although the MRP system was a considerable progression in planning and scheduling, it was not perfect. A few flaws led to manufacturing errors, such as wrong data integrity, wrong manufacturing results if the manufacturing capacity was not in the same place, or the manufacturing plans that do not consider manufacturing capacity availability (not constrained resource quantity).

If the input data was not actual (outdated IR or BOMs data), it caused the inaccurate system output. That means that the system was not self-check the input data, and all data always had to be controlled.

Another case that is suitable to mention is the possible IR mistakes when there is one system for more manufacturing localities. When the system does not divide each manufacturing place, MRP could include stock status from one place into the manufacturing schedule calculation in another place far away from this stock.

The next common main issue of MRP is also the absence of capacity planning. Yes, MRP made a WO list, but these orders do not consider manufacturing resources' availability. That means that if the necessary resource such as some workplace, machines, or control center is busy, the whole WO schedule will crash.

These troubles usually cost much money for each business, and it was soon necessary to implement new models. This implementation led to the emergence of the new system called Manufacturing Resource Planning (MRP II).[1][5]

1.2 Manufacturing Resource Planning (MRP II)

The core of the new system was the concept of the previous MRP system. There was an improvement of existing models as better Inventory tracking or more advanced Master scheduling. However, the main difference between MRP and MRP II are new additional models. This system's idea aimed to involve new functional areas, which have not been before in MRP. These areas mainly contain Machine Capacity Scheduling, General Accounting, and Human Resourcing. All of them are connected to the MPS and determining the constraints to the whole calculation. Thanks to these modules' feedback, the MRP II system can make simulations based on various input data and provide more specific and accurate output data than simpler MRP. Financial and accounting modules bring into this system the basics of budgeting and business financial system planning.

Improvement in Inventory tracking and Capacity scheduling led to the significant amelioration in system output results. If the system considers manufacturing resources' availability, the real manufacturing times meet the planned ones. Complications occur if some unexpected incidents happened. Changes in customer orders, lack of workers (absence due to illness), failures of Facility, or sudden shortage of material, require rescheduling of the manufacturing schedule. In the complex manufacturing system, it is not easy to solve such problems in the MRP II system environment due to vast numbers of items or numbers and processes' complexity. The APS system replaces the system flaws, which this thesis describes later.

If someone speaks about MRP, it probably means MRP II because the original MRP is already not commonly used in the stand-alone version. MRP II comes into the subconscious of companies in the 1980'. [5][6]

1.3 Enterprise resource planning (ERP)

In 1990 a new product called ERP had appeared on the market with Business systems. It was the same system as MRP II, which was on the market from 1980. However, this system has become an excellent system to manage the whole manufacturing and even non-manufacturing company during these ten years. This improvement led to the new system name: Enterprise resource planning.

Picture 1-3: ERP System [7]

As seen in the picture (see Picture 1-3), the ERP system is management software, which integrates into a single system every essential department and its systems such as MRP, Human Resource Management, Customer Relationship Management (CRM), Financial Management, and Supply Chain Management. All departments like Human Resources, Purchasing, Planning, Sales, Production, Accounting, Marketing, and more can share information in real-time with each other. In this case, every employee of any company department has access to the latest and actual data (which is needed), and the department's collaboration is synchronized. Ideally, everybody gets the right data to the right place and the right time. HR (Human Resources) can easily manage the data about the current employees or newcomers. PLN (Planning Department) through the ERP system gets the overview of the budget, PRD (Production) has information about the latest BOMs of finished products, the PUR (Purchase Department) has an overview of the current status of on-hand stocks, delivery, and so on. Nowadays, the most used systems and the leaders in ERP system markets are SAP, ORCL, or MSFT. [7][8][9]

Although the ERP system is indispensable for most companies worldwide, the scheduling issue of sudden unexpected incidents persisted. The complex manufacturing system's rescheduling is an inconvenience that a different planning system must solve.

1.4 Advanced Planning and Scheduling (APS)

Two words that are involved in the system's name, are very similar but different. The significant disparity is the question that these two terms answer, in other words, where time and money are lost during the process.[33]

- **Planning**

Planning is the first step of the whole process, which determines the path to achieve a result, and answers WHAT and HOW are needed.[33]

- **Scheduling**

The next step of the process is Scheduling. For the schedule making, it is necessary to have a plan from the previous step. That means that the schedule is made based on the plan, but the plan cannot be made based on the schedule. During the scheduling process, the plan is subject to analysis to determine WHEN and WHO will be involved.[33]

For example, in manufacturing, it is first necessary to identify the orders and suborders in-house requests. It means to determine the primary path to achieve a result during the first stage (Planning).

WHAT

- Order request
- Sub-orders of in-house requests

HOW

- Company departments
- Company manufacturing resources

Next, this primary path must be determined to the detailed schedule (Scheduling), which considers the due dates, manufacturing capacity, constraints of manufacturing, and the workload. Then, it is possible to identify and sort the necessary manufacturing and nonmanufacturing tasks chronologically.

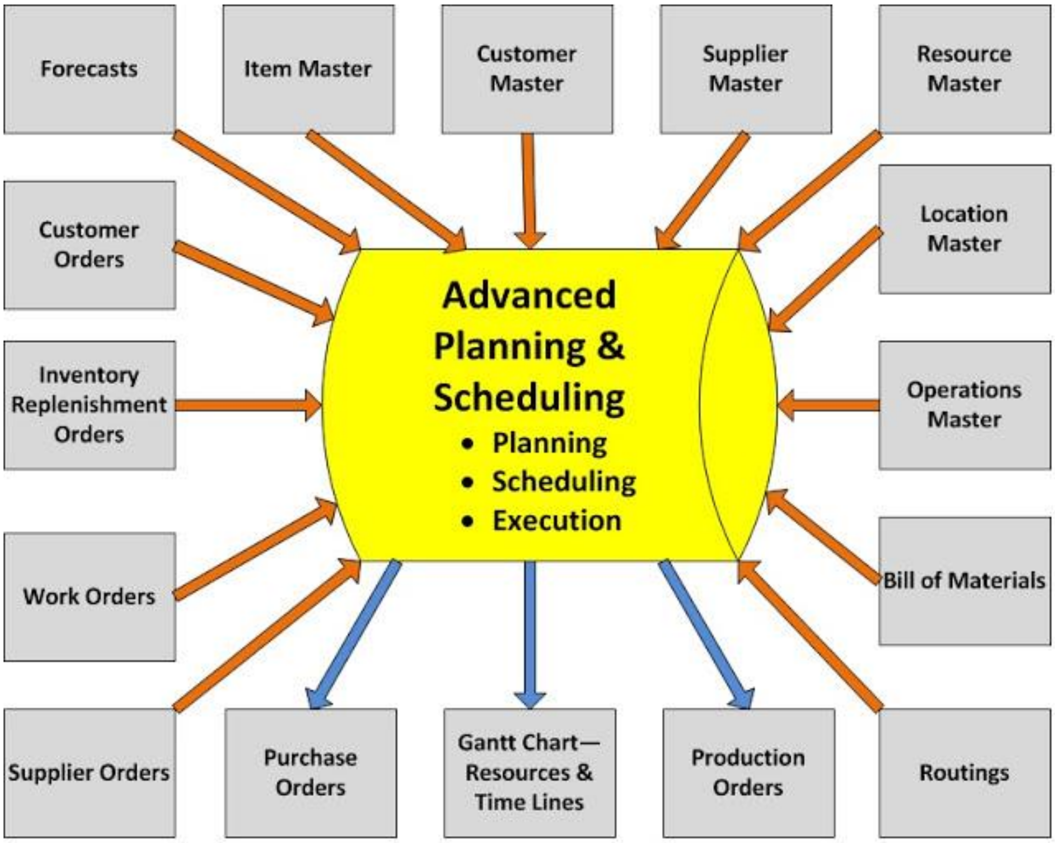
WHEN

- Due dates
- Project's milestones terms

WHO

- Specific resources (based on capacity and current workload)
- Responsible persons

Stand-alone Planning has several issues that must be optimized by the schedule. The plan does not consider the workload of manufacturing capacity by other orders. It leads to the overload of workshops or wasting by waiting. On the other hand, the schedule manages the production timing to achieve the highest possible manufacturing and logistic efficiency. [33]



Picture 1-4: Advanced Planning and Scheduling [10]

Advanced planning and scheduling systems do not replace but supplement the ERP system (the APS system using the ERP system's data). It provides real-time data about the current situation to the planner and his action's future effects.

Generally, the ERP system is a transaction system. It means that all tasks are using the respective standard specific transaction, which moves the data from the system data warehouse to the user or vice versa. A disadvantage of the transaction systems is the inability to analyze and determine impacts caused by the order change. On the other hand, the APS system is not a transaction system; thus, it can perform the mentioned analysis, determine impacts of changes and calculate the optimal solution according to manufacturing constraints, workload, material availability, due dates, and resource capacity. For this calculation, the APS system using the data from the ERP system.[34]

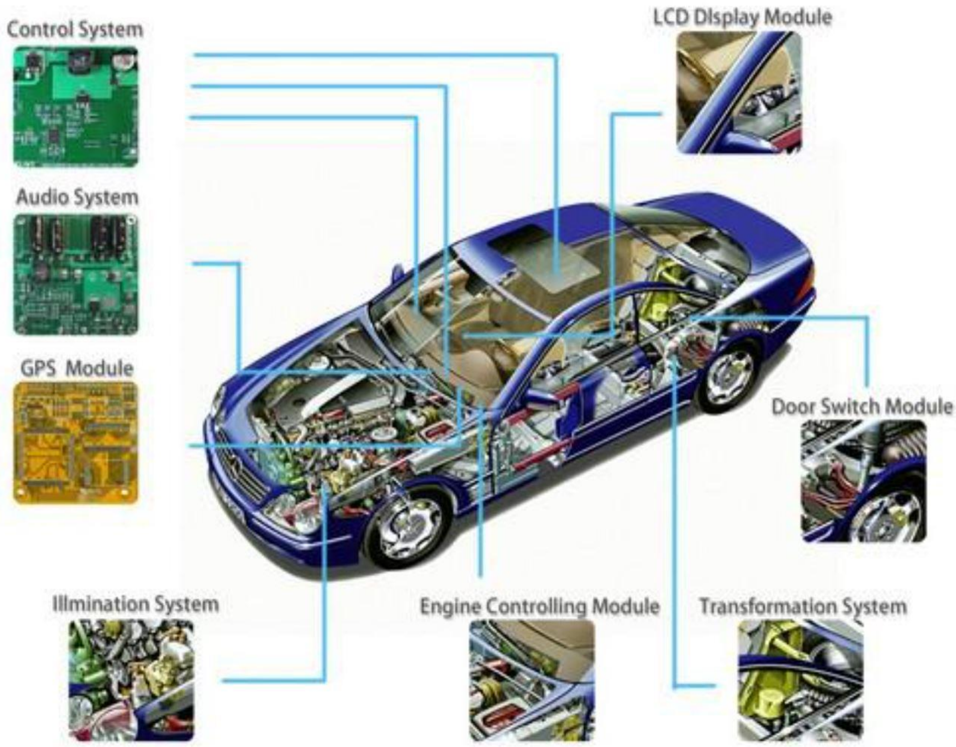
With APS, the planner's work can be much more useful than the MRP II planning system. While in MRP II any necessary manufactory reschedules due to unexpected sudden incidents had to be solved manually. In APS, all these steps are performing automatically, and the planning activities can focus on developing and analyzing the possible scenarios.

APS system operates with a significant amount of data from the ERP system, such as mentioned BOM, MPS, IR, and other outputs from MRP II and ERP systems (see Picture 1-4). Based on such data, the APS can forecast each workplace's workload, impact on capacity, or due dates by unexpected incidents, which leads to the making of different possible scenarios. These scenarios consider constrained capacity, the concept of Theory of constraints (restructuring the whole manufacturing system according to system constrain), and forward or backward planning and scheduling.

As was mentioned, there are two ways to make a manufacturing schedule. Firstly, Forward planning and scheduling calculate the date when it will be possible to fulfill the order. Secondly, Backward planning and scheduling calculate the date when the production must begin to fulfill the order (Just in time (JIT)). Combining these planning and scheduling methods allows sorting of manufacturing orders according to priority or another criterium.[11][12][13]

2 Introduction into the client's assignment

Nowadays, automotive development requires modern electronic technologies. Most of the electronic operations are performed by the PCBs (printed circuit boards), with which this thesis deals.



Picture 2-1: PCB systems in vehicle [36]

Thanks to the electricity of the entire car system, the performance of the vehicle is increasing. Some of improvements are immediately recognizable as video displays, audio systems, or air conditioning. The hidden ones are working on the car crew's security during the ride and car safety during the parking—for example, airbags, collision avoidance systems, autonomous driving, or radar monitoring. Fuel-saving by the engine control unit is also suitable to mention. [31][35]

In current modern vehicles, there are about 200 control units such as sensors and processors. It means that together with this development of new technologies, production methods must also be evolving.

2.1 Client company

The client company supplies the world car manufacturers with Charging stations, In-vehicle displays, Head-up displays, or the vehicle wireless mobile phone chargers in high volume. Therefore, advanced SMT lines are necessary to allow for such a high quantity of production.

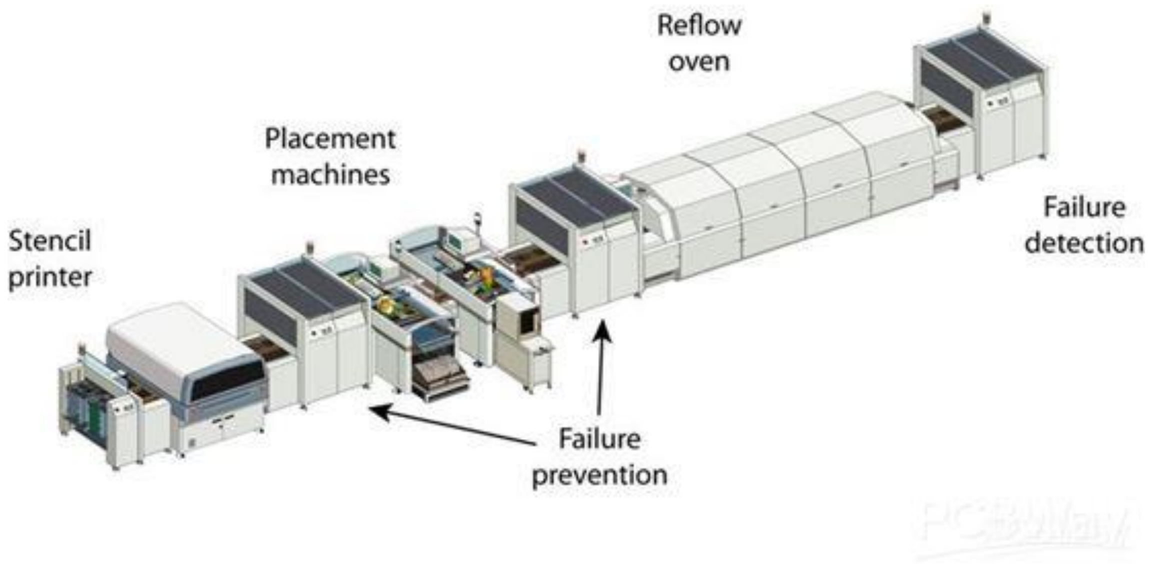
Picture 2-2: SMT line [32]

2.2 Surface Mount Technology (SMT)

Surface Mount Technology (SMT) is a method for Surface mount device (SMD) assembly on the printed circuit board (PCB) by automated machines. It is the most common electronic assembling method in the electronic industry. [27]

The process of SMT is dividing into three following main subprocesses.

- Soldering paste applying
- Mounting of SMD on PCB
- Soldering of the PCB



Picture 2-3: SMT line [28]

2.2.1 Soldering paste applying

First of all, it is necessary to apply the soldering paste on the printed circuit board. For this purpose, it is using the silkscreen method with the laser-cut stainless-steel stencil. During the printing process, the soldering paste leaves a trail on the board's required places through the stencil. Each stencil is used for the specific board, which means that each project needs an inherent stencil. If the process finishes, the PCB must be checked before the next assembly step to avoid wasting by the defects. In case when the inspection confirms PCB as OK, the Mounting of SMD follows. [27][28]

2.2.2 Mounting of SMD on PCB

Into the placement machine enters the checked PCBs from inspection and also the SMDs. The mounting device takes SMDs from the trays or reels (supplemented according to the manufacturing schedule) by the vacuum or gripper nozzle and places it on the PCB in the right position at high speed. This whole mounting process is tracked by the visual system, which takes care of each component's correct location. The second inspection follows after the mounting of all parts. The Pick and place machines are the most expensive part of the whole SMT line. Its initial cost is about 60-70% of the entire SMT line cost. [27][28]

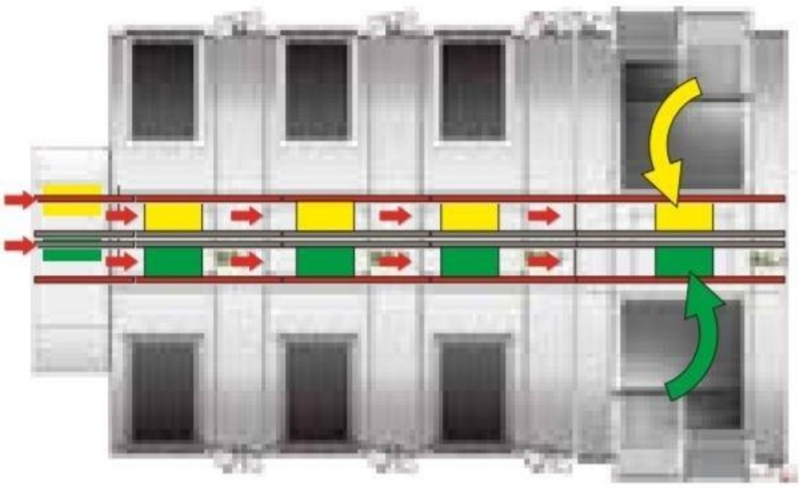
2.2.3 Soldering of the PCB

For soldering of PCB could use two methods.

- Reflow-soldering
- Vapor phase soldering

The reflow-soldering process is warming the PCBs in the nitrogen atmosphere until the soldering paste melts. During the cooling process, the soldering paste creates a connection with SMDs. It is usually using for manufacturing series orders. On the other hand, it is more suitable for more accurate manufacturing and more sensitive SMDs to use the Vapor phase soldering process. This process allows the preferable regulation of soldering temperature and excludes possible damage to components by high temperature.[27][28]

A client's SMT machine for which this thesis designs the model is specified by the dual-line functionality. Thanks to this machine modification, it is possible to assembly two different products or more of one simultaneously (see Picture 2-3). It is primarily suitable for two types of orders: high mix and low volume, low mix, and high volume.



Picture 2-3: SMT dual-line functionality [36]

For better understanding the exemplary layout of dual-line SMT machines is attached (see Appendix no.1)

2.3 Specification of the client's assignment

As was mentioned, the client's company puts the new SMT line in operation, including dual rails. In the scheduling of the line, it is necessary to consider both rails as independent sources, which influence each other.

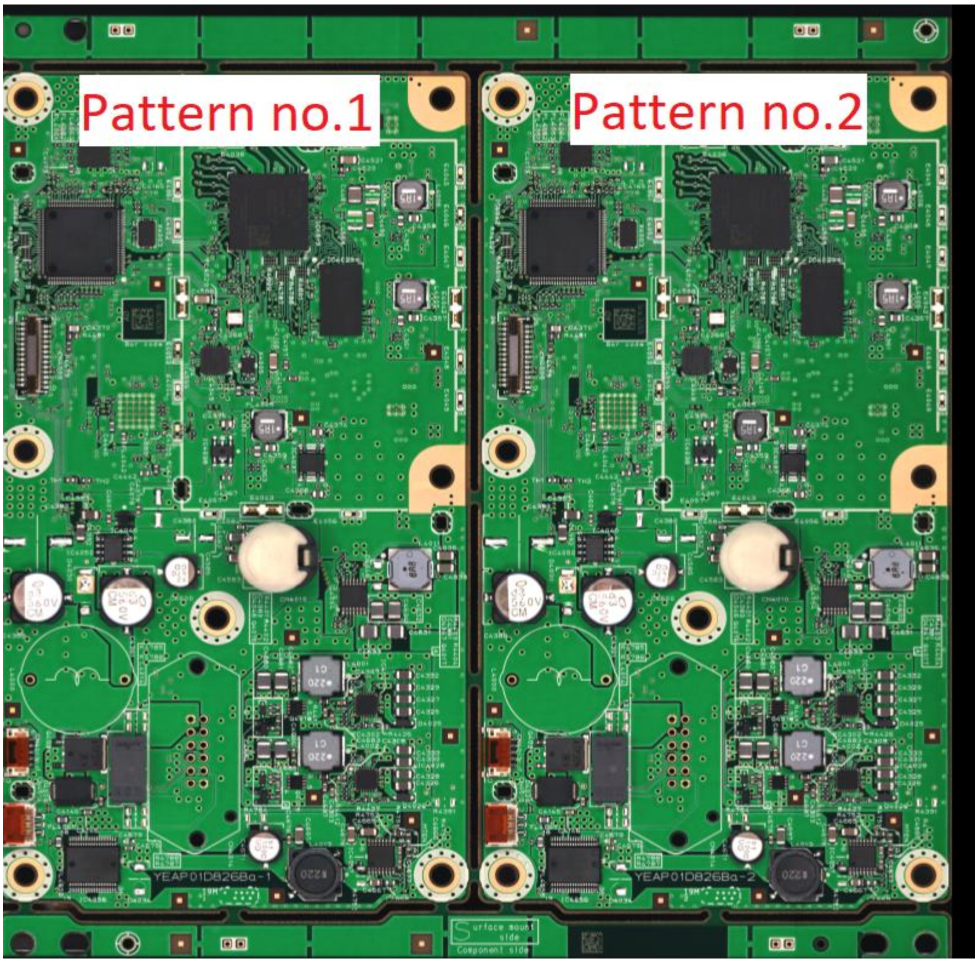
This influence is caused by the model mix, which can be produced at the same time. If the first trail produces a specific product, the second trail can make products only from the model mix belonging to the first trail product. These constraints are arising due to limited machine positions for the SMD trays or reels. It leads to the model mix, which requires the same SMD.

The second factor influencing dual rails is the takt time (the rate needed to complete a product). There are two types of takt times.

- Takt time for sheet
- Takt time for pattern

It is appropriate to specify the meaning of these two terms.

- Pattern - PCB board of the final product
- Sheet - PCB frame holding the patterns



Picture 2-4: PCB sheet

Therefore, the smallest production batch is one sheet. If this sheet includes more than one pattern, it is impossible to make only one pattern stand alone. So, the takt time for the sheet is naturally multiple of pattern quantity and the pattern takt time.

As was mentioned, the takt time of the first trail product influences the takt time on the second trail. These times must be summed into the one coupled takt time.

For example, imagine the two products, A and B. Sheet A includes one pattern and sheet B two patterns. Takt time of the pattern is 20 seconds for A and 30 seconds for B. It means sheet takt time 20 seconds for A and 60 seconds for B. However, the takt time for both sheets is 80 seconds as a sum of both sheet takt times (see Table 2-1).

Example no.1	Trail no.1	Trail no.2	Unit
Process	A	B	
Pattern takt time	20	30	sec
Pattern QTY	1	2	
Sheet takt time	20	60	sec
Final sheet takt time	80	80	sec
Final pattern takt time	80	40	sec

Table 2-1: Example no.1

Of course, the client's SMT line has its bottleneck. In this case, the reflow oven. It constrains the flow of PCB sheets to a minimum takt time of 30 seconds. It means that even if the Place and pick machine could produce with takt time under 30 seconds, the sheets' flow will not be faster (see Table 2-2).

Example no.2	Trail no.1	Trail no.2	Unit
Process	A	No production	
Pattern takt time	20		sec
Pattern QTY	1		
Sheet takt time	20		sec
Final sheet takt time	30		sec
Final pattern takt time	30		sec

Table 2-2: Example no.2

3 Groundwork of the simulation

Before the client's productive system simulation, it is suitable to make a sample model with more straightforward input data. The simulation is made using the APS system provided by the co-researcher company Aimtec a.s.

3.1 Aimtec

Aimtec a.s. as the co-researcher is an original Pilsen company with over twenty years of experience in the digital factory concept. Its digitalization services of manufacturing and logistics use many companies worldwide to keep up with the pace of future changes.

An essential product from Aimtec's offer for this thesis is an APS system. APS is one of the company's several products, and it is built on the Asprova APS system. Currently, Aimtec is the only distributor company of Asprova APS software in the Czech Republic, according to the official Asprova websites.[29][30]

Picture 3-1: Aimtec a.s. [29]

3.2 ASPROVA

One of the APS systems is ASPROVA from the same name japan company Asprova Corporation (see Picture 2-1). This system can plan long-term and short-term schedules at high speed for manufacturing orders in multiple processes, inventory and purchase plans, and integrated sales, based on ERP data.

Picture 3-2: Asprova Corporation [14]

The main benefits which are suitable to mention in comparison with MRP II are:

- Visual management
- Inventory reduction
- Lead time reduction

3.2.1 Visual management

To visually manage the production, Asprova using the Gant Chart. This chart involves the schedule of all orders from the current situation to the coming several months. It gives the planner an overview of the manufacturing schedule based on ERP (for example, SAP system) data and provides accurate delivery date quotations. It is also possible to make several scenarios and react to sudden incidents by various measures to avoid late deliveries and unfilled orders.

In this visual management, the planner can quickly identify the whole system's bottleneck resource and, according to, restrict the entire system. It reduces work in progress and ties capital in the material, which is undoubtedly visible in the Gant chart. This chart displays the workload of the manufacturing system's resources in working shifts, such as machines, workplaces, workers, or tools in an organized way. For better control, the planner can move with each process in the time and resources axis by mouse drag.

Further, the Gant chart also includes the Load Graph, which displays each resource's workload in time. Thanks to this, the company, for example, can reduce or increase the number of workers in advance and save money. Another dynamic graph in the Gant chart is an Inventory graph. It displays the current inventory levels or its forecast according to the manufacturing schedule at each manufacturing time. Thanks to this, the planner gets an overview of onhand stock and its reaction to his possible scenarios.[15]

3.2.2 Inventory reduction

Streamlining of the scheduling by the Asprova APS system leads to the shorten production lead times. It reduces Work in Progress, which means saving of tied money in necessary stocks and the possibility of their more efficient use. To keep the safety stock, Asprova can place a manufacturing order just in time whenever there is a possibility of a drop below the safety stock level. In this way, the system keeps an inventory to a minimum while avoids overproduction. [16]

3.2.3 Lead time reduction

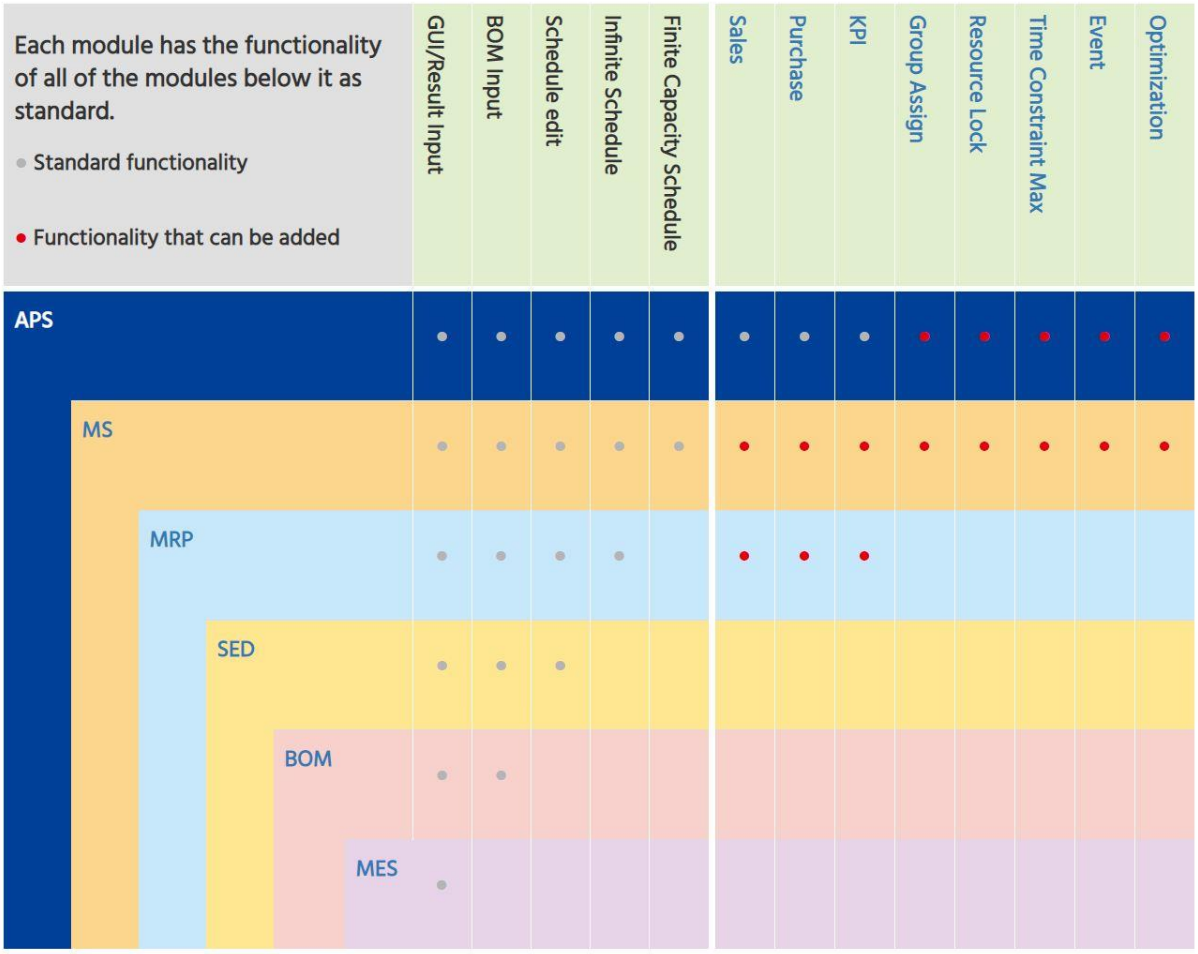
Asprova system offers the lead time reduction by synchronizing processes or by process splitting into several resources. It causes relief for overloaded resources and more effective use of other waiting resources. Also, it is possible to reduce the transfer of batch sizes. For this lead time reduction, the Asprova APS system offers the following processes relationships.

- ES (End - Start) - determines the start of the next process according to the previous process's end.
- SS (Start - Start) - determines the start of the next process according to the previous process's start.
- SSEE (Start - Start - End - End) - determines the start of the previous process to the start of the next, and the end of the previous process to the end of the next.
- EES (End Every - Start) - determines the start of the next process, including several operations from one previous process to achieve just in time delivery.
- ESE (End - Start Every) - determines the start of the next process from the previous process, including several operations to achieve just in time delivery.

It is also possible to set the resource constraints as the Time Control MAX, which determines the maximum wait time between processes (the product will degrade if the schedule will separate subsequent processes longer than is needed). [17]

3.2.4 Asprova modules

Asprova APS system includes several models, namely APS, MS, MRP, SED, BOM, and MES (see Picture 3-2).



Picture 3-3: Module table [24]

- **Manufacturing Execution System (MES)**

MES is an APS submodule for displaying the current plan and the results in real-time manufacturing workplaces. This module provides all output in clear reports and graphs, allows inputting results but does not allow any changes in the schedule.[18]

- **Bill of material (BOM)**

BOM module includes all features of the MES module plus the BOM inputting. It is useful that providing the new products, BOMs are possible to upload from an excel file. Due to this compatibility, there are no mistakes due to data differences.[19]

- **Schedule Editor (SED)**

This SED module allows more production planners to modify the production schedule simultaneously. It is useful if the same manufacturing capacity is used by independent planners who do not cooperate (to eliminate overlapping).[20]

- **Material Resource Planning (MRP)**

The MRP in the APS system provides the calculation for the long term and short term schedule material requirements. There is no possibility of optimizing manufacturing orders, and the whole estimate is under infinite capacity conditions. It also includes the previous modules. Companies commonly using an external MRP system from ERP simultaneously with APS. It causes the unsynchronized purchase plans with the work instructions. The APS data must be uploaded into ERPs MRP and conversely (this process needs another planner interface). It is complicated, and there is a lot of options to make a possible mistake. Thus, it is proper to eliminate ERP MRP and further use the APS MRP for all calculations.[21]

- **Manufacturing Scheduler (MS)**

MS is a planning module that calculates with Finite manufacturing capacity, provides the planning solution for each resource, and determine the work instruction.[22]

- **Advanced Planning and Scheduling (APS)**

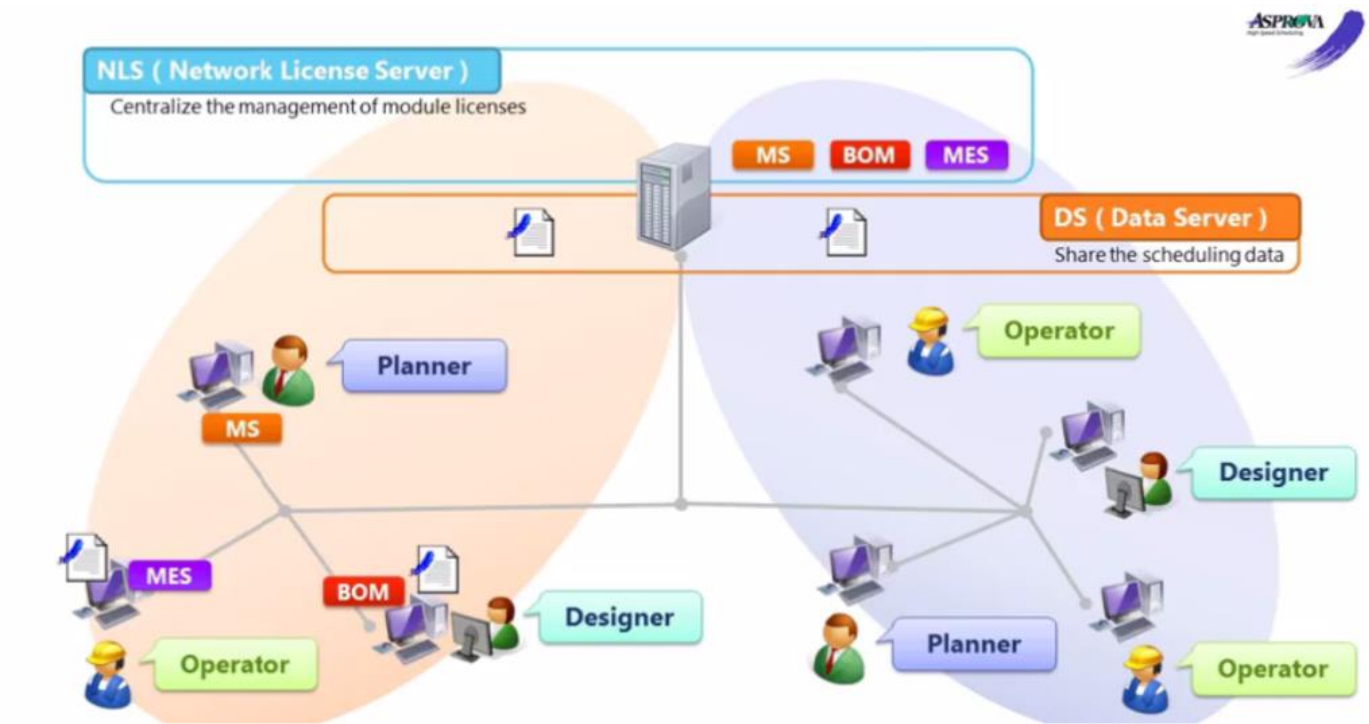
The APS is the MS plus Sales Option plus Purchase Option. It manages the scheduling of all steps from purchase to dispatch and involving all mentioned modules.[23]

- **Network License Server (NLS)**

Network License Server is using for managing module licenses across the company network.[25]

- **Data Server (DS)**

DS integrates all data using the Data Server to share the newest data across the modules efficiently. [25]



Picture 3-4: Network modules [26]

4 Sample model designing

To achieve the valid form results for application to the productive system, the model must fulfill some conditions. As mentioned in the previous chapters, the fundamental client's request is to create an APS system algorithm for the new dual rail SMT line. The further clarification of the client's request depends on the first version of the sample model, therefore, the model guideline has to be established.

4.1 Suggested sample model guideline

Although this model should correspond to the client's production system, it is appropriate to make the model simple for possible modifications according to future demands. For this purpose, the following guideline is designed.

Guideline

- Create sample data for the simulation.
- Automate the data import to the Asprova APS.
- Set the necessary parameters for further commands.
- Create the function that executes the assignment between the orders according to the model mix.
- Modify the order's production time.
- Execute the schedule and evaluate the model results.

Model conditions

- Instead of one dual-rail SMT line with two sources, set two monorail SMT lines with one source.
- Neglect the sheet and pattern tact time with its multiplication; consider the pattern tact time equal to the sheet tact time.
- Modify the shorter order's production time according to the longer order's production time in the pair; do not summarize the tact times.
- Neglect all bottlenecks and do not optimize the line production.
- Execute all orders by their quantity.

The sample data must contain the necessary information about the production items, orders, and processes, filling the four Asprova tables, namely the Item table, Order table, Process table, and the Integrated master editor table.

- Each item is specified in the Item table by the Item code with the Model mix attribute containing the items that can be produced simultaneously.

- The Order table involves the quantity (QTY) of each ordered item together with its due date. This table is further used as a base table for the assigning function.

- Processes are specified in the Process table by the Process code and Process name.

- The Integrated master editor table incorporates the spreadsheets of items and processes with the required resources and production time.

First of all, it is necessary to create sample data that will be imported into the Asprova APS (in this case Microsoft excel software is used). For this migration the correct data form is required.

The mentioned data upload from the database into the system could be executed either manually, which is feasible but unwanted due to possible human errors, or automatically. However, this automatic data upload from the excel file requires an additional driver, which allows the connection between the excel database and Asprova software. Such driver can be, for example, the CData ODBC.

After installing the CData ODBC driver, it is necessary to make a configuration and set the resource database excel file. Then, in the Asprova user interface, it is necessary to set the connection between the internal tables and the external database. This determination uses the Data I/O table and allows the defining correspondences between internal and external objects.

Further, the SMT lines are set according to the guideline as two independent sources. Calendar data as shifts time etc., is not important for this model, so the original settings are sufficient.

According to the model mix, each available ordered item must be assigned into the pair with another most suitable item. The executing function has to be specified in the command editor interface. Suppose it is executed by the QTY descending rule of order where the item from the model mix is searched by the closest ordered QTY.

After the assignment of the item, the next step is to put pairs into groups. First of all, it is necessary to allow the group assignment in the project settings and set the group type in the Group type table. There are four group types:

- **n/a:** No grouping
- **Same start time:** Assigns grouped operations to 1 resource so that their production start times are the same.
- **Same start on other resources:** Assigns grouped operations to different resources so that their production start times are the same.
- **Continuous:** Grouped operations are assigned to be continuous on the same main resource.

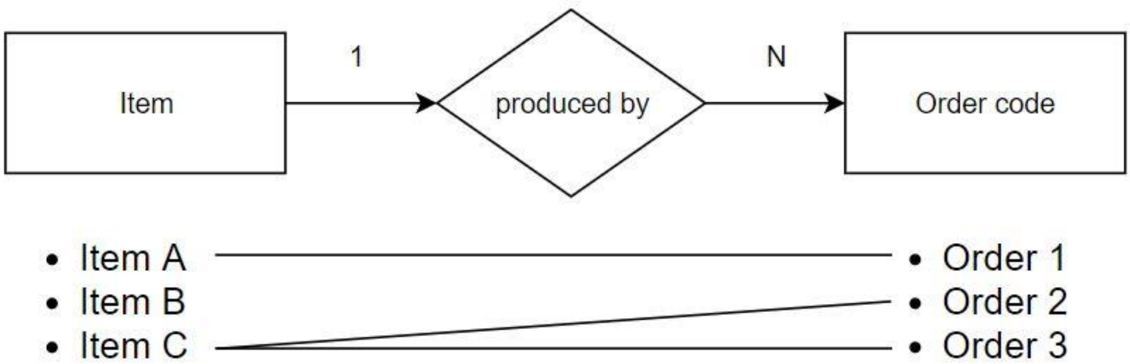
The specific code must specify each pair's group to avoid miscalculation due to the same group names. It is suitable to define a new command for this purpose, which will assign particular group code to each item pair.

Such settings of the new project should be appropriate to achieve the results fitting for the next simulations.

4.2 Data importing

According to the suggested sample model, the sample data (see Appendix no.2) fill the three basic required tables: The Order table, Integrated master editor table, and the Item table.

The Order table must contain for the further operations data such as the Order code (which is considered as a primary key) with its Item name (orders final product), quantity, and the due date. After the data is uploaded through the CData software, the Order table looks like in the following picture (see Picture 4-2). From the table, it is obvious that each order can include only one Item, and the Item can be processed by one or more orders (different due dates or customers). Naturally, the item does not have to be processed by any orders (see Picture 4-1).



Picture 4-1: Item/Order code ER diagram

As the data about the orders' priority was not determined in the excel database, the Asprova sets the universal value to eighty (higher value represents more important orders).

	Order code	Item	Order quantity	Due date	Priority
1	⊞ 1	A	26	01/05/2021 00:00:00	80
2	⊞ 2	B	9	02/05/2021 00:00:00	80
3	⊞ 3	C	58	03/05/2021 00:00:00	80
4	⊞ 4	D	160	04/05/2021 00:00:00	80
5	⊞ 5	A	99	05/05/2021 00:00:00	80
6	⊞ 6	B	77	06/05/2021 00:00:00	80
7	⊞ 7	C	116	07/05/2021 00:00:00	80
8	⊞ 8	D	48	08/05/2021 00:00:00	80
9	⊞ 9	E	111	09/05/2021 00:00:00	80
10	⊞ 10	F	54	10/05/2021 00:00:00	80
11	⊞ 11	G	11	11/05/2021 00:00:00	80
12	⊞ 12	H	80	12/05/2021 00:00:00	80
13	⊞ 13	I	77	13/05/2021 00:00:00	80
14	⊞ 14	J	2	14/05/2021 00:00:00	80
15	⊞ 15	K	18	15/05/2021 00:00:00	80
16	⊞ 16	L	45	01/05/2021 00:00:00	80
17	⊞ 17	M	39	02/05/2021 00:00:00	80
18	⊞ 18	N	78	03/05/2021 00:00:00	80
19	⊞ 19	O	89	04/05/2021 00:00:00	80
20	⊞ 20	A	34	05/05/2021 00:00:00	80
21	⊞ 21	B	13	06/05/2021 00:00:00	80
22	⊞ 22	C	26	07/05/2021 00:00:00	80
23	⊞ 23	D	13	06/05/2021 00:00:00	80
24	⊞ 24	E	2	07/05/2021 00:00:00	80
25	⊞ 25	F	17	08/05/2021 00:00:00	80
26	⊞ 26	A	114	09/05/2021 00:00:00	80
27	⊞ 27	B	17	10/05/2021 00:00:00	80
28	⊞ 28	C	0	11/05/2021 00:00:00	80
29	⊞ 29	D	10	03/05/2021 00:00:00	80
30	⊞ 30	A	85	13/05/2021 00:00:00	80
31	⊞ 31	B	18	14/05/2021 00:00:00	80
32	⊞ 32	C	28	15/05/2021 00:00:00	80
33	⊞ 33	D	93	01/05/2021 00:00:00	80
34	⊞ 34	E	54	06/05/2021 00:00:00	80
35	⊞ 35	P	4	07/05/2021 00:00:00	80
36	⊞ 36	Q	27	08/05/2021 00:00:00	80
37	⊞ 37	R	10	13/05/2021 00:00:00	80
38	⊞ 38	S	73	14/05/2021 00:00:00	80
39	⊞ 39	T	80	15/05/2021 00:00:00	80
40	⊞ 40	U	120	01/05/2021 00:00:00	80
41	⊞ 41	V	68	06/05/2021 00:00:00	80
42	⊞ 42	W	92	07/05/2021 00:00:00	80
43	⊞ 43	X	2	08/05/2021 00:00:00	80
44	⊞ 44	Y	15	09/05/2021 00:00:00	80
45	⊞ 45	Z	79	10/05/2021 00:00:00	80
46	⊞ 46	T	10	11/05/2021 00:00:00	80
47	⊞ 47	U	15	12/05/2021 00:00:00	80
48	⊞ 48	V	11	13/05/2021 00:00:00	80
49	⊞ 49	W	195	14/05/2021 00:00:00	80
50	⊞ 50	X	18	15/05/2021 00:00:00	80
51	⊞ 51	Y	100	01/05/2021 00:00:00	80
52	⊞ 52	Z	85	02/05/2021 00:00:00	80

Picture 4-2: Order table (a)

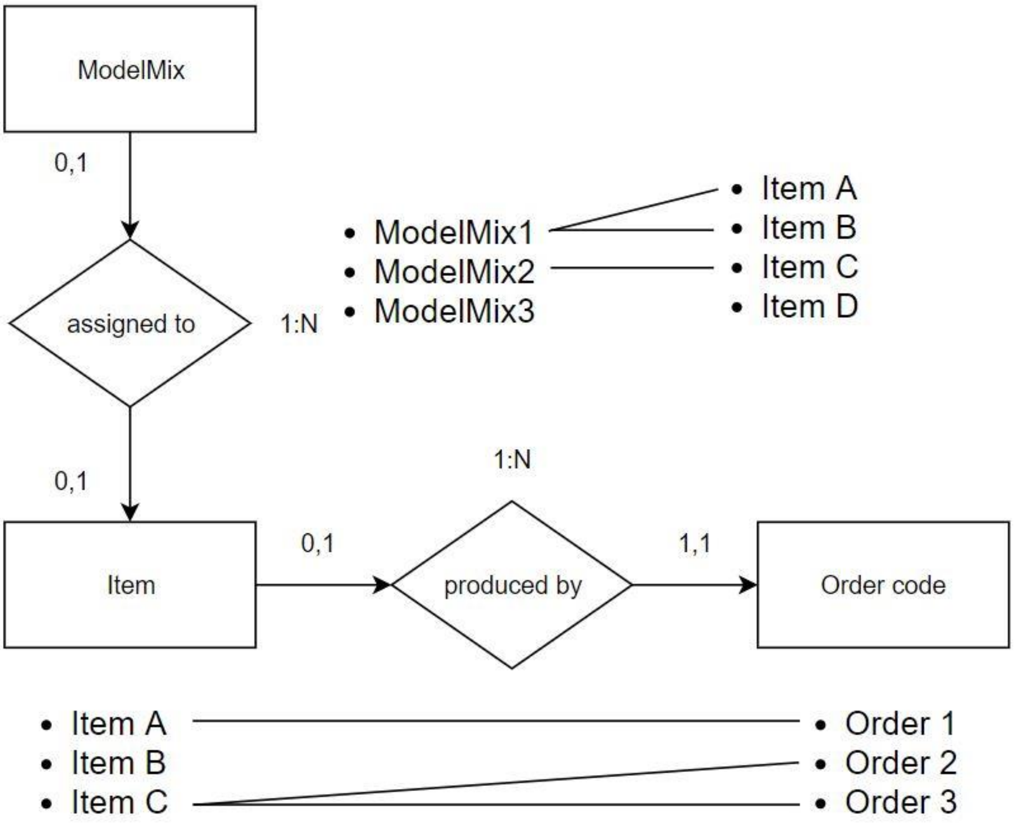
The next uploaded database table is the Item table (see Picture 4-2). This table is important for further operations regarding the order's assignment into the pairs according to the model mix. Before the data import, the ModelMix column has to be firstly created in the Asprova system.

	Item code	ModelMix
1	⊞A	B;H;M
2	⊞B	C;A;M
3	⊞C	D;B
4	⊞D	C;U
5	⊞E	
6	⊞F	G
7	⊞G	F
8	⊞H	I;A
9	⊞I	H
10	⊞J	K
11	⊞K	J;Z
12	⊞L	
13	⊞M	A;B
14	⊞N	O
15	⊞O	N
16	⊞P	R
17	⊞Q	R
18	⊞R	P;Q
19	⊞S	U;W
20	⊞T	
21	⊞U	S;D
22	⊞V	W
23	⊞W	V;S
24	⊞X	Y
25	⊞Y	X
26	⊞Z	K

Picture 4-3: Item table

To better understand how the entities are linked it is suitable to demonstrate the relationship in the ER diagram (see Picture 4-4).

The Integrated master editor has no impact on the pair assigning function, but it is necessary for the schedule. For this sample the following simple processes for each item are sufficient (see Picture 4-5). The input material is processed in the mounting process, which leads to the final product.



Picture 4-4: ModelMix/Item ER diagram

Picture 4-5: Model process - Graphical master

The picture (see Picture 4-6) shows that every item is composed of a stand-alone mounting process. In this example the material input (Input instruction) and the manufacturing (Use instruction) with its codes are the same for all items. Production time for this model is randomly assigned, and the Setup time with the Teardown is neglected.

The confusing information could be the SMT resource, which is the same for all items. According to the suggested guideline, the orders in pairs should be produced simultaneously on two resources. The answer is that this mentioned SMT resource is a group of resources that displays the Resource table (see Picture 4-7). According to this group, the Asprova APS system can assign the process to its available source. That means that until no adjusting conditions determine which line is producing, the orders are produced as soon as possible on all available sources. However, such conditions are neglected at this moment and will be specified during the programming.

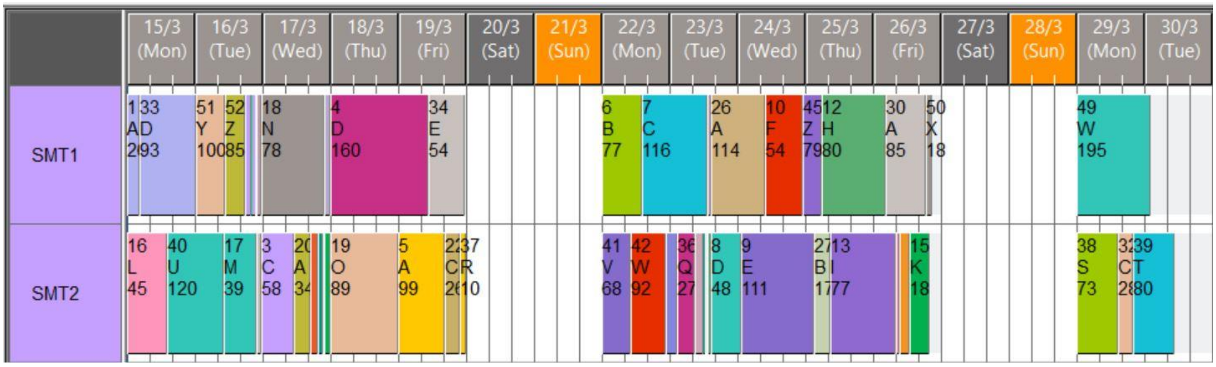
	Item	Process number	Process code	Instruction type	Instruction code	Resource/Item	Previous process nu	Setup	Production	Teardown
1	A	10	Mounting	Input instruc	In	A-Material				
2				Use instructi	M	SMT			10mp	
3	B	10	Mounting	Input instruc	In	B-Material				
4				Use instructi	M	SMT			11mp	
5	C	10	Mounting	Input instruc	In	C-Material				
6				Use instructi	M	SMT			12mp	
7	D	10	Mounting	Input instruc	In	D-Material				
8				Use instructi	M	SMT			13mp	
9	E	10	Mounting	Input instruc	In	E-Material				
10				Use instructi	M	SMT			14mp	
11	F	10	Mounting	Input instruc	In	F-Material				
12				Use instructi	M	SMT			15mp	
13	G	10	Mounting	Input instruc	In	G-Material				
14				Use instructi	M	SMT			16mp	
15	H	10	Mounting	Input instruc	In	H-Material				
16				Use instructi	M	SMT			17mp	
17	I	10	Mounting	Input instruc	In	I-Material				
18				Use instructi	M	SMT			18mp	
19	J	10	Mounting	Input instruc	In	J-Material				
20				Use instructi	M	SMT			19mp	
21	K	10	Mounting	Input instruc	In	K-Material				
22				Use instructi	M	SMT			20mp	
23	L	10	Mounting	Input instruc	In	L-Material				
24				Use instructi	M	SMT			19mp	
25	M	10	Mounting	Input instruc	In	M-Material				
26				Use instructi	M	SMT			18mp	
27	N	10	Mounting	Input instruc	In	N-Material				
28				Use instructi	M	SMT			17mp	
29	O	10	Mounting	Input instruc	In	O-Material				
30				Use instructi	M	SMT			16mp	
31	P	10	Mounting	Input instruc	In	P-Material				
32				Use instructi	M	SMT			15mp	
33	Q	10	Mounting	Input instruc	In	Q-Material				
34				Use instructi	M	SMT			14mp	
35	R	10	Mounting	Input instruc	In	R-Material				
36				Use instructi	M	SMT			13mp	
37	S	10	Mounting	Input instruc	In	S-Material				
38				Use instructi	M	SMT			12mp	
39	T	10	Mounting	Input instruc	In	T-Material				
40				Use instructi	M	SMT			11mp	
41	U	10	Mounting	Input instruc	In	U-Material				
42				Use instructi	M	SMT			10mp	
43	V	10	Mounting	Input instruc	In	V-Material				
44				Use instructi	M	SMT			9mp	
45	W	10	Mounting	Input instruc	In	W-Material				
46				Use instructi	M	SMT			8mp	
47	X	10	Mounting	Input instruc	In	X-Material				
48				Use instructi	M	SMT			7mp	
49	Y	10	Mounting	Input instruc	In	Y-Material				
50				Use instructi	M	SMT			6mp	
51	Z	10	Mounting	Input instruc	In	Z-Material				
52				Use instructi	M	SMT			5mp	

Picture 4-6: Integrated master editor table

	Resource code	Resource name	Resource groups	Resource class	Resource type	Resource quantity constraints
1	SMT1	SMT1	SMT	Simple resour	Main resour	Constrained
2	SMT2	SMT2	SMT	Simple resour	Main resour	Constrained
3	SMT			Simple resour	Operation g	Not constrained

Picture 4-7: Resource table

After rescheduling (Asprova function), all orders were scheduled as processes into the Gantt chart. No error appeared, which means that the data was imported correctly. However, from the picture (see picture 4-8) it is obvious that the production is far from ideal (the orders are produced as soon as possible on all available sources). Thus, the pair assigning function has to be specified to establish an order in the scheduling.



Picture 4-6: Gantt chart (a)

4.3 Assigning into the pair

For creating the pairs it is necessary to specify the appropriate assigning function. This assignment aims not to make the pairs between the items but between the orders.

In the Item table, there are Item codes with the model mix or without. Items with no model mix will be considered in pair with themselves, and the pairs of the items with the model mix will be set with the most suitable item from the model mix. Mentioned suitability lies in its order QTY. The function aim is to pair QTYs with the smallest difference in the absolute value according to the model mix.

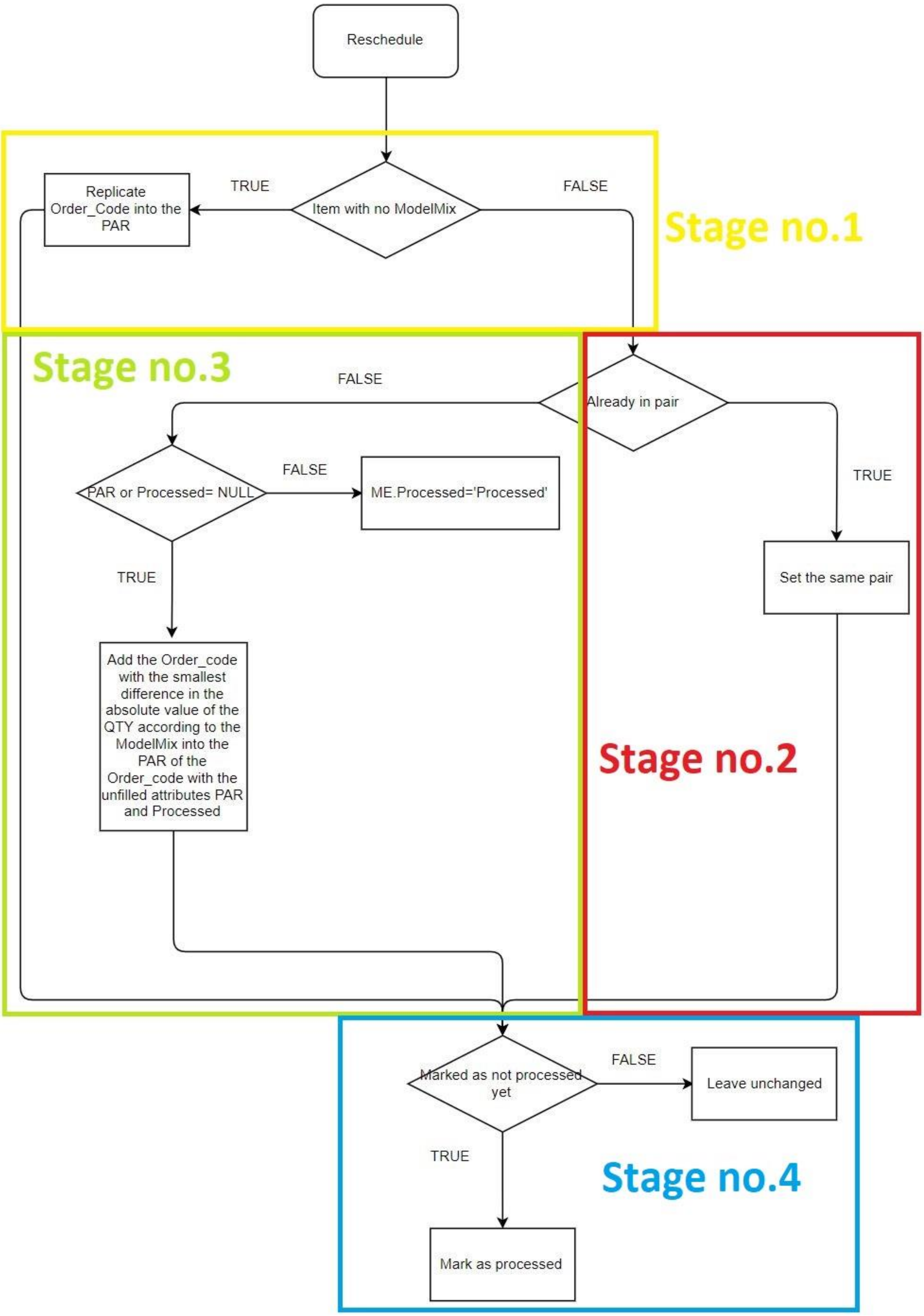
After a closer look, it is obvious that this model includes four following types of pairs:

- An order item with its model mix
- An order item without its model mix
- An order item with its model mix, but without any available orders, inclusive items from the model mix
- An order that is already in the previous pair

The function's execution, which comprises mentioned conditions, leads to creating the order pairs but does not set the operation pairs. For this purpose, the function has to be divided into the Order expression (modification of the Order table) and the Operation expression (modification of the Operation table and the Gantt chart).

4.3.1 Order expression

For the function's smooth operation two new attributes in the Order table, namely "PAR" and "Processed" has to be created. Into the attribute "PAR", the function assigns the order codes according to the model mix. The model mix data are filled into the PAR cell only if there is unprocessed available order from the same model mix. It leads to the function looping and the end of the algorithm.



Picture 4-7: Order expression - Flow chart

For this reason, it was determined there is a need for the second attribute, the "Processed". This attribute is filled after the function execution for each processed order code, whether the function found any order code to assignment or not. Thanks to this feature, the algorithm knows which orders were already processed, thereby eliminated the function looping.

According to the model guideline and the conditions set up in this chapter the flow chart for the order expression was developed (see Picture 4-9). This chart shows well the three basic ways to achieve the "processed" result.

- An item with no model mix (Stage no.1).
- An order that is already assigned to the other pair (Stage no.2).
- The main function finding the ideal pair (Stage no.3).

Each of the mentioned ways ends in the "processed" status (Stage no.4).

Stage no.1

The first stage of the script verifies if the order's item has its model mix.

```
If(!FValid(ME.Item.ModelMix),
      ME.PAR=ME.Code,
      NEXT STAGE)
```

If the order's item has no model mix, it replicates the current orders code into the PAR. Otherwise, it continues to the next stage.

Stage no.2

The second stage of the script verifies if the order is already included in some previous pair. If the result is TRUE, it set the same (reverse) pair. Otherwise, it continues to the next stage.

```
If(ExistIF('Order',
               TARGET.PAR==ME.Code),
      ME.PAR=MinObjectIF('Order',
                         TARGET.PAR==ME.Code,
                         TARGET.PAR).Order_Code,
      NEXT STAGE)
```

Step no.3

The third stage is the fundamental of the whole function because it finds the most suitable order code into the pair with the current order that has a model mix and not processed status.

If the attribute PAR or Processed is NULL, it marks the order as "processed". Otherwise, it adds the manufacturing Order code with the smallest difference in the absolute value of the QTY according to the ModelMix into the PAR of the Order_code with the unfilled attributes PAR and Processed.

```
If(!FValid(ME.PAR)||!FValid(ME.Processed),
         ME.PAR=MinObjectIF(PROJECT.Child['Order'].Child,
                           TARGET.Order_Type=='M'
                               && !FValid(TARGET.OrderUser_Processed)
                               && Find(TARGET.Order_Item.ModelMix,
                                       ME.Item)
&&!FValid(TARGET.OrderUser_PAR_Order),
                           Abs(ME.Qty-TARGET.Order_Qty)).Order_Code,
         ME.Processed='Processed')
```

Stage no.4

The fourth stage marks each processed order as "processed", whether the function found any order code to assign. Unlike the previous stages, this stage is executed in the stand-alone order expression.

```
If(!FValid(ME.Processed),
   ME.Processed='Processed',0)
```

4.3.2 Operation expression

After the execution of the Order expression, the pairs were set. For the Operation expression it is required to set the same start time. Such settings are defined in the Group type table as an Assing method, in this case, "Same start time on other resources"(see Picture 4-10).

	Code	Assign method	Assign operation group	Continuous sort expression
1	⊞ Same start time	Same start time on oth	Yes	Work Code[1].a
*				

Picture 4-8: Group type table

This Assign method allows setting the same start time for selected operations. The selection should be proceeded according to the pairs created by the Order expression in the Order table. From that it is clear that the Operation expression has to set the pairs group type as "Same start time on other resources" and determine for each pair unique operation group. According to this operation group, the Asprova recognizes which operations have to start at the same time.

The function creating the pair in the operations according to the pair in the orders is divided into two expressions.

The first expression assigns the operation group to the operation pairs according to its order code. As was already mentioned, the order code is a primary key; therefore, it can be used as a unique mark for the operation group. Therefore, the operation group, is equal to the lower order code from the pair.

```
ME.UGroup=MinValue(ME.Order.Code,ME.Order.PAR)
```

The second expression fills the operations group type in pairs as a "Same start time on other resources".

```
ME.GroupType=If(!FValid(ME.Order.PAR),0,'Same start time')
```

Property	Value
49:10	49:10
Type	Operation
Master operation	Mounting
Process number	10
Main output item	W
Production quantity	195
Quantity fixed level	0
Time fixed flag	☐
Resource fixed flag	Unfixed
User specified quantity	
User specified quantity fixed level	
User specified setup time	
User specified production time	
User specified teardown time	
User specified EST	
User specified LET	
User specified main resource	
User specified operation group	38
User specified group type	Same start time
Starting order	

General | Split | Assignment | Results | Evaluation | KPI | Link | Common | Interna

Picture 4-9:General properties of the operation (a)

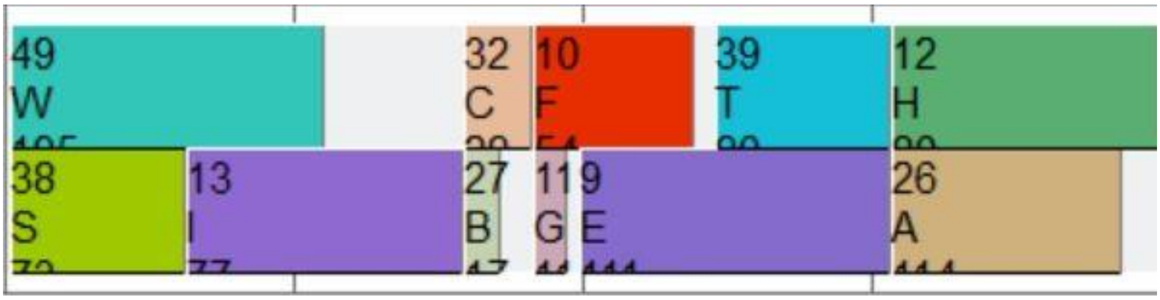
The picture (see Picture 4-11) shows the operation's General properties after the function execution. The user-specified group type is assigned the "same start time" value, and the user-specified operation group is equal to the lower order code in the pair. In this case, order no. 49 is in the pair with the order no. 38. Thus, the operation group is also equal to 38.

Although the pairs' function is set, two types of order operations with incorrectly set group types are remaining.

- Orders in the pair with themselves.
- Orders in the pair with no orders.

First mentioned has no model mix. The second one has its model mix, but there is no other order remaining for the assignment. It is common for both types to stay stand-alone in pairs, and it cannot be set as the same start time group.

What happens with the schedule if it is rescheduled after the function execution is obvious (see Picture 4-12).



Picture 4-10: The incorrect assign

The pairs' orders start simultaneously as was required, for example, order 49(W) with 38(S). However, the unpaired orders, in this case, 13(I), 9(E), 39(T) were scheduled into the free capacity of the sources. It leads to the unwanted following pairs.

- 49(W) - 13(I)
- 10(F) - 9(E)
- 39(T) - 9(E)

Additional stage

To eliminate these pairs, it is necessary to set only one available source (SMT1) for the unpaired orders. It is proceeded by the specification of the resource (see Picture 4-13).

	Resource code	Resource name	Spec 1	Resource groups	Resource class	Resource type	Resource quantity constraints
1	SMT1	SMT1	SMT;SMT1	SMT	Simple resource	Main resour	Constrained
2	SMT2	SMT2	SMT	SMT	Simple resource	Main resour	Constrained
3	SMT				Simple resource	Operation g	Not constrained
*							

Picture 4-11: Resource table / Specification

The mentioned specification must also be assigned to orders if they could be produced on the SMT group (the order pairs) or only on the SMT1 (stand-alone orders). It is executed by the additional stage in the order expression.

```
ME.Spec1=If(!FValid(ME.PAR)||ME.PAR==ME.Code,'SMT1','SMT')
```

This expression sorts the orders to the relevant source according to the participation in pairs.

4.3.3 Script

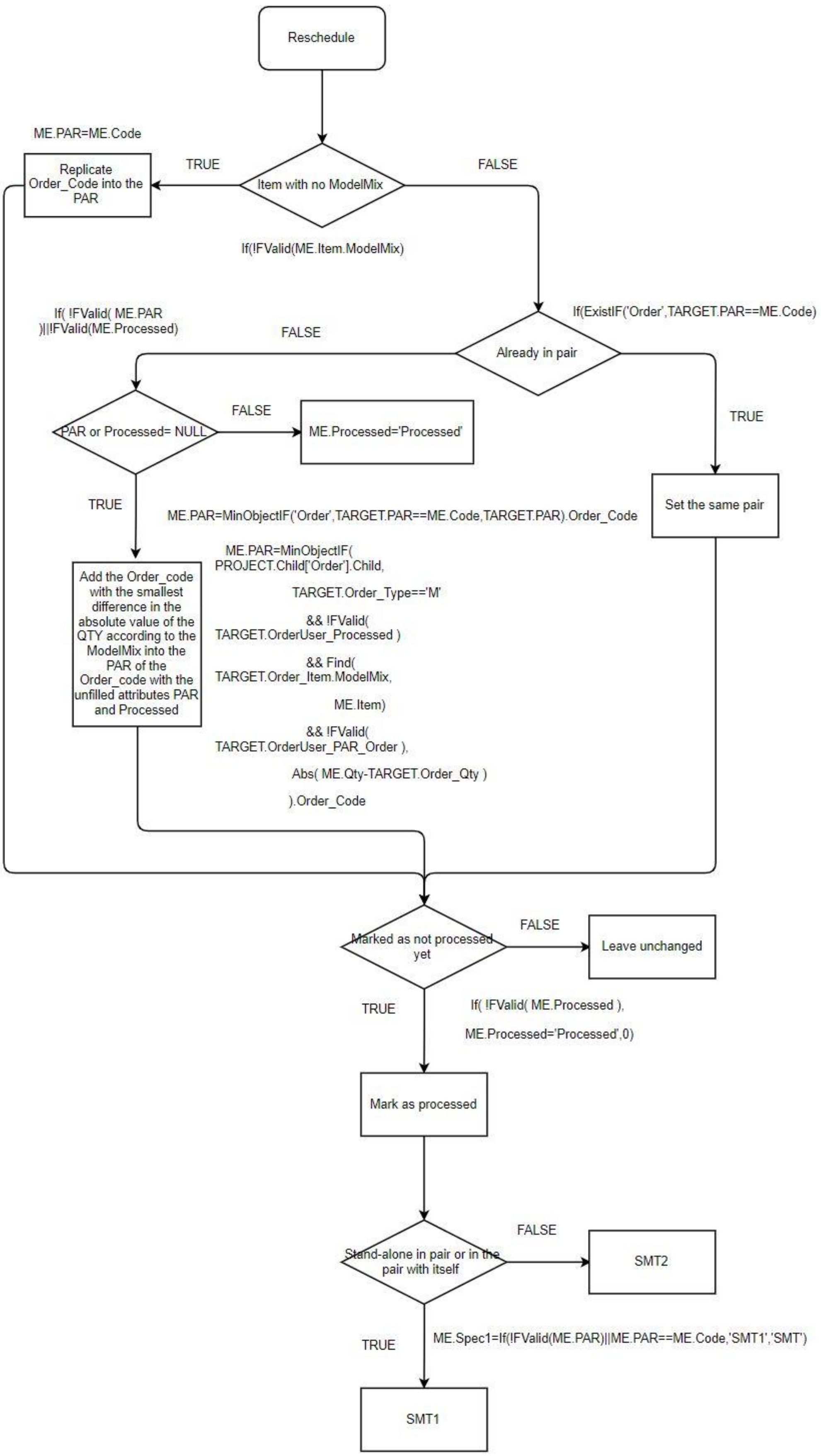
Order expression

```
If(!FValid( ME.Item.ModelMix),
   ME.PAR=ME.Code,
   If( ExistIF('Order',
               TARGET.PAR==ME.Code),
      ME.PAR=MinObjectIF('Order',
                         TARGET.PAR==ME.Code,
                         TARGET.PAR).Order_Code,
      If(!FValid(ME.PAR)||!FValid(ME.Processed),
         ME.PAR=MinObjectIF(PROJECT.Child['Order'].Child,
                            TARGET.Order_Type=='M'
                                && !FValid(TARGET.OrderUser_Processed)
                                && Find(TARGET.Order_Item.ModelMix,
                                        ME.Item)
&&!FValid(TARGET.OrderUser_PAR_Order),
                            Abs( ME.Qty-TARGET.Order_Qty )
                           ).Order_Code,
         ME.Processed='Processed'
        )
     )
  );
If(!FValid(ME.Processed),
   ME.Processed='Processed',0);
ME.Spec1=If(!FValid(ME.PAR)||ME.PAR==ME.Code,'SMT1','SMT')
```

Operation expression

```
ME.UGroup=MinValue(ME.Order.Code,ME.Order.PAR)
;
ME.GroupType=If(!FValid(ME.Order.PAR),0,'Same start time');
```

4.3.4 Order expression flow chart



Picture 4-12:Order expression flow chart

4.3.5 Function results

According to the set model guideline, the created pairing function's execution filled the order table (see Picture 4-15) and the already mentioned general properties of each operation (see Picture 4-11).

	Order code	PAR	Processed	Spec 1	Item	Order quantity	Due date	Priority
1	⊞ 1	21	Processed	SMT	A	26	01/05/2021 00:00:00	80
2	⊞ 2	28	Processed	SMT	B	9	02/05/2021 00:00:00	80
3	⊞ 3	8	Processed	SMT	C	58	03/05/2021 00:00:00	80
4	⊞ 4	40	Processed	SMT	D	160	04/05/2021 00:00:00	80
5	⊞ 5	6	Processed	SMT	A	99	05/05/2021 00:00:00	80
6	⊞ 6	5	Processed	SMT	B	77	06/05/2021 00:00:00	80
7	⊞ 7	33	Processed	SMT	C	116	07/05/2021 00:00:00	80
8	⊞ 8	3	Processed	SMT	D	48	08/05/2021 00:00:00	80
9	⊞ 9	9	Processed	SMT1	E	111	09/05/2021 00:00:00	80
10	⊞ 10	11	Processed	SMT	F	54	10/05/2021 00:00:00	80
11	⊞ 11	10	Processed	SMT	G	11	11/05/2021 00:00:00	80
12	⊞ 12	26	Processed	SMT	H	80	12/05/2021 00:00:00	80
13	⊞ 13		Processed	SMT1	I	77	13/05/2021 00:00:00	80
14	⊞ 14		Processed	SMT1	J	2	14/05/2021 00:00:00	80
15	⊞ 15	52	Processed	SMT	K	18	15/05/2021 00:00:00	80
16	⊞ 16	16	Processed	SMT1	L	45	01/05/2021 00:00:00	80
17	⊞ 17	30	Processed	SMT	M	39	02/05/2021 00:00:00	80
18	⊞ 18	19	Processed	SMT	N	78	03/05/2021 00:00:00	80
19	⊞ 19	18	Processed	SMT	O	89	04/05/2021 00:00:00	80
20	⊞ 20	31	Processed	SMT	A	34	05/05/2021 00:00:00	80
21	⊞ 21	1	Processed	SMT	B	13	06/05/2021 00:00:00	80
22	⊞ 22	23	Processed	SMT	C	26	07/05/2021 00:00:00	80
23	⊞ 23	22	Processed	SMT	D	13	06/05/2021 00:00:00	80
24	⊞ 24	24	Processed	SMT1	E	2	07/05/2021 00:00:00	80
25	⊞ 25		Processed	SMT1	F	17	08/05/2021 00:00:00	80
26	⊞ 26	12	Processed	SMT	A	114	09/05/2021 00:00:00	80
27	⊞ 27	32	Processed	SMT	B	17	10/05/2021 00:00:00	80
28	⊞ 28	2	Processed	SMT	C	0	11/05/2021 00:00:00	80
29	⊞ 29	47	Processed	SMT	D	10	03/05/2021 00:00:00	80
30	⊞ 30	17	Processed	SMT	A	85	13/05/2021 00:00:00	80
31	⊞ 31	20	Processed	SMT	B	18	14/05/2021 00:00:00	80
32	⊞ 32	27	Processed	SMT	C	28	15/05/2021 00:00:00	80
33	⊞ 33	7	Processed	SMT	D	93	01/05/2021 00:00:00	80
34	⊞ 34	34	Processed	SMT1	E	54	06/05/2021 00:00:00	80
35	⊞ 35		Processed	SMT1	P	4	07/05/2021 00:00:00	80
36	⊞ 36	37	Processed	SMT	Q	27	08/05/2021 00:00:00	80
37	⊞ 37	36	Processed	SMT	R	10	13/05/2021 00:00:00	80
38	⊞ 38	49	Processed	SMT	S	73	14/05/2021 00:00:00	80
39	⊞ 39	39	Processed	SMT1	T	80	15/05/2021 00:00:00	80
40	⊞ 40	4	Processed	SMT	U	120	01/05/2021 00:00:00	80
41	⊞ 41	42	Processed	SMT	V	68	06/05/2021 00:00:00	80
42	⊞ 42	41	Processed	SMT	W	92	07/05/2021 00:00:00	80
43	⊞ 43	44	Processed	SMT	X	2	08/05/2021 00:00:00	80
44	⊞ 44	43	Processed	SMT	Y	15	09/05/2021 00:00:00	80
45	⊞ 45		Processed	SMT1	Z	79	10/05/2021 00:00:00	80
46	⊞ 46	46	Processed	SMT1	T	10	11/05/2021 00:00:00	80
47	⊞ 47	29	Processed	SMT	U	15	12/05/2021 00:00:00	80
48	⊞ 48		Processed	SMT1	V	11	13/05/2021 00:00:00	80
49	⊞ 49	38	Processed	SMT	W	195	14/05/2021 00:00:00	80
50	⊞ 50	51	Processed	SMT	X	18	15/05/2021 00:00:00	80
51	⊞ 51	50	Processed	SMT	Y	100	01/05/2021 00:00:00	80
52	⊞ 52	15	Processed	SMT	Z	85	02/05/2021 00:00:00	80

Picture 4-13: Order table (b)

As the order table shows, the order pairs are set, each order is processed no matter if it is in the pair, and each order is categorized into the resource groups SMT and SMT1.

4.4 Set the same production time function

Further, it is necessary to modify the operations production time to the same value for each pair's operation. However, such a command needs the data from the previous function. Thus, it has to proceed after it is rescheduled. The command sequence should be, therefore, as follows.

- **Assigning into the pair**
  - ⇒ Prepare for assignment
  - ⇒ Filter orders
  - ⇒ Upload operations
  - ⇒ Modify properties

- **Default scheduling parameter**
  - ⇒ Prepare for assignment
  - ⇒ Filter orders
  - ⇒ Unassign all
  - ⇒ Explode orders
  - ⇒ Group operations
  - ⇒ Assign privileged operations
  - ⇒ Assign time fixed operations
  - ⇒ Assign result constrained operations
  - ⇒ Assign/peg orders
  - ⇒ Adjustment
  - ⇒ Evaluate schedule
  - ⇒ Beep

- **Set the same production time**
  - ⇒ Upload operations
  - ⇒ Modify properties

- **Default scheduling parameter**
  - ⇒ Prepare for assignment
  - ⇒ Filter orders
  - ⇒ Unassign all
  - ⇒ Explode orders
  - ⇒ Group operations
  - ⇒ Assign privileged operations
  - ⇒ Assign time fixed operations
  - ⇒ Assign result constrained operations
  - ⇒ Assign/peg orders
  - ⇒ Adjustment
  - ⇒ Evaluate schedule
  - ⇒ Beep

The first function is the function created from the previous chapter when the mentioned script is implemented into the "Modify properties" command. Further, after this is executed it is necessary to execute the "Default scheduling parameter" command to schedule and calculate all required information linked to the schedule.

When it is done, the order codes were paired into the operation groups with the same start time. Further, the Default scheduling parameter made a schedule with the production time calculated according to its QTY and the Integrated master editor table data. Its results are to be found in the Operation table. (see Picture 4-16).

	Production start time	Code	Main outpu	Production qu	Main resource	Production end time	Production time
1	15/03/2021 00:00:00	⊞1:10	A	26	SMT1	15/03/2021 04:20:00	15600S
2		⊞21:10	B	13	SMT2	15/03/2021 02:23:00	8580S
3	15/03/2021 04:20:00	⊞16:10	L	45	SMT1	15/03/2021 18:35:00	51300S
4	15/03/2021 18:35:00	⊞33:10	D	93	SMT1	16/03/2021 14:44:00	72540S
5		⊞7:10	C	116	SMT2	16/03/2021 17:47:00	83520S
6	16/03/2021 14:44:00	⊞24:10	E	2	SMT1	16/03/2021 15:12:00	1680S
7	16/03/2021 15:12:00	⊞35:10	P	4	SMT1	16/03/2021 16:12:00	3600S
8	16/03/2021 16:12:00	⊞14:10	J	2	SMT1	16/03/2021 16:50:00	2280S
9	16/03/2021 17:47:00	⊞40:10	U	120	SMT1	17/03/2021 13:47:00	72000S
10		⊞4:10	D	160	SMT2	18/03/2021 04:27:00	124800S
11	17/03/2021 13:47:00	⊞34:10	E	54	SMT1	18/03/2021 02:23:00	45360S
12	18/03/2021 02:23:00	⊞46:10	T	10	SMT1	18/03/2021 04:13:00	6600S
13	18/03/2021 04:27:00	⊞50:10	X	18	SMT1	18/03/2021 06:33:00	7560S
14		⊞51:10	Y	100	SMT2	18/03/2021 14:27:00	36000S
15	18/03/2021 06:33:00	⊞25:10	F	17	SMT1	18/03/2021 10:48:00	15300S
16	18/03/2021 10:48:00	⊞48:10	V	11	SMT1	18/03/2021 12:27:00	5940S
17	18/03/2021 14:27:00	⊞17:10	M	39	SMT1	19/03/2021 02:09:00	42120S
18		⊞30:10	A	85	SMT2	19/03/2021 04:37:00	51000S
19	19/03/2021 04:37:00	⊞28:10	C	0	SMT1	19/03/2021 04:37:01	1S
20		⊞2:10	B	9	SMT2	19/03/2021 06:16:00	5940S
21	19/03/2021 06:16:00	⊞15:10	K	18	SMT1	19/03/2021 12:16:00	21600S
22		⊞52:10	Z	85	SMT2	19/03/2021 13:21:00	25500S
23	19/03/2021 13:21:00	⊞29:10	D	10	SMT1	19/03/2021 15:31:00	7800S
24		⊞47:10	U	15	SMT2	19/03/2021 15:51:00	9000S
25	19/03/2021 15:51:00	⊞20:10	A	34	SMT1	19/03/2021 21:31:00	20400S
26		⊞31:10	B	18	SMT2	19/03/2021 19:09:00	11880S
27	19/03/2021 21:31:00	⊞43:10	X	2	SMT1	19/03/2021 21:45:00	840S
28		⊞44:10	Y	15	SMT2	19/03/2021 23:01:00	5400S
29	22/03/2021 00:00:00	⊞18:10	N	78	SMT1	22/03/2021 22:06:00	79560S
30		⊞19:10	O	89	SMT2	22/03/2021 23:44:00	85440S
31	22/03/2021 23:44:00	⊞3:10	C	58	SMT1	23/03/2021 11:20:00	41760S
32		⊞8:10	D	48	SMT2	23/03/2021 10:08:00	37440S
33	23/03/2021 11:20:00	⊞5:10	A	99	SMT1	24/03/2021 03:50:00	59400S
34		⊞6:10	B	77	SMT2	24/03/2021 01:27:00	50820S
35	24/03/2021 03:50:00	⊞22:10	C	26	SMT1	24/03/2021 09:02:00	18720S
36		⊞23:10	D	13	SMT2	24/03/2021 06:39:00	10140S
37	24/03/2021 09:02:00	⊞41:10	V	68	SMT1	24/03/2021 19:14:00	36720S
38		⊞42:10	W	92	SMT2	24/03/2021 21:18:00	44160S
39	24/03/2021 21:18:00	⊞36:10	Q	27	SMT1	25/03/2021 03:36:00	22680S
40		⊞37:10	R	10	SMT2	24/03/2021 23:28:00	7800S
41	25/03/2021 03:36:00	⊞12:10	H	80	SMT1	26/03/2021 02:16:00	81600S
42		⊞26:10	A	114	SMT2	25/03/2021 22:36:00	68400S
43	26/03/2021 02:16:00	⊞10:10	F	54	SMT1	26/03/2021 15:46:00	48600S
44		⊞11:10	G	11	SMT2	26/03/2021 05:12:00	10560S
45	26/03/2021 15:46:00	⊞27:10	B	17	SMT1	26/03/2021 18:53:00	11220S
46		⊞32:10	C	28	SMT2	26/03/2021 21:22:00	20160S
47	29/03/2021 00:00:00	⊞9:10	E	111	SMT1	30/03/2021 01:54:00	93240S
48	30/03/2021 01:54:00	⊞45:10	Z	79	SMT1	30/03/2021 08:29:00	23700S
49	30/03/2021 08:29:00	⊞13:10	I	77	SMT1	31/03/2021 07:35:00	83160S
50	31/03/2021 07:35:00	⊞38:10	S	73	SMT1	31/03/2021 22:11:00	52560S
51		⊞49:10	W	195	SMT2	01/04/2021 09:35:00	93600S
52	31/03/2021 22:11:00	⊞39:10	T	80	SMT1	01/04/2021 12:51:00	52800S

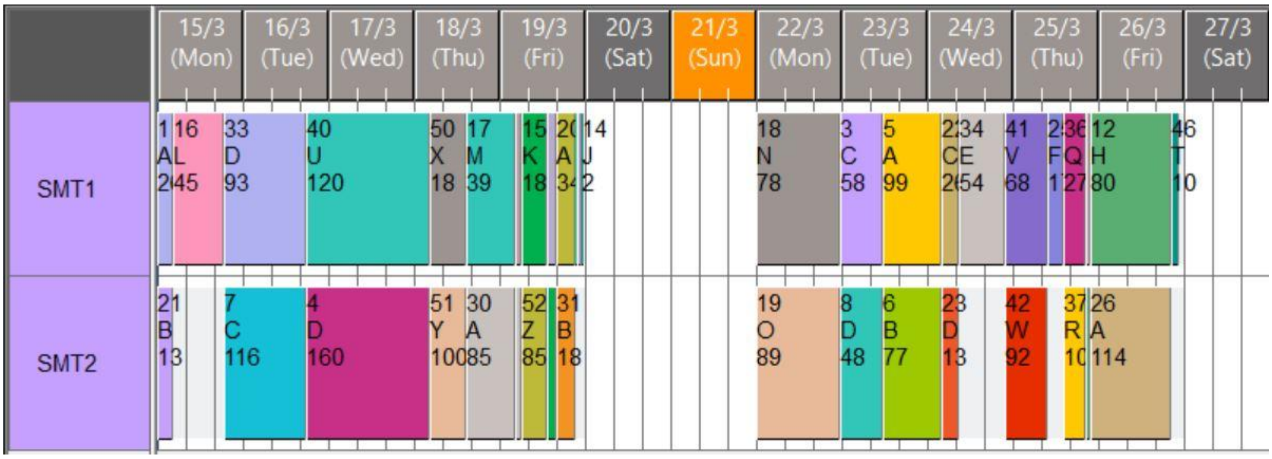
Picture 4-14: Operation table (a)

In this table all the necessary information about each operation is shown. At this moment, the operations are grouped according to their start time, which was already set. The items respond to the orders and their model mix, production QTY responds to the order table, and the main resource responds to the resource setup. Further, the system calculates the production time according to the QTY and the one-piece production time. This production time is important for another modification because it requires the same value according to the model guideline.

Once we have the resulting data it is the right time to modify the same production time in the operations pairs. This modification is also performed in the "Modify properties" command, but now in the “Set the same production time” function.

4.4.1 Set the same production time – option A

This function determines the pair's operation with the longer production time, and according to that, sets the same value to the (shorter) second order. It follows that the pair's order with the longest production time remains unchanged, and to this value is equal the production time of the shorter operation. For better understanding it is suitable to state the graphical representation of the problematics in the Gantt chart (see Picture 4-17).



Picture 4-15: Set the same production time Gantt chart

To achieve this result required and viewed above in the Gantt chart (for the full view, see Appendix no. 3a), it is necessary to create a script into the mentioned "Modify properties" command. Such function should be in the following form.

```
ME.Work_UProductionTime=MaxIF('Order',
              TARGET.Operations.UGroup==ME.UGroup,
              TARGET.Operations.OperationProductionTime);
```

The function sets the production time to the same value under the same operation group's condition according to the pair's longer production time.

Such modification filled the operations' property named User specified production time (see Picture 4-19) in the General properties for both operations in the pair. After another reschedule and execution of the Default scheduling parameter, these values are imported into the Operation table (see Picture 4-18)

	Production start time	Code	Main outpu	Produc tion qu	Main resource	Production end time	Production time
1	15/03/2021 00:00:00	⊞1:10	A	26	SMT1	15/03/2021 04:20:00	15600S
2		⊞21:10	B	13	SMT2	15/03/2021 04:20:00	15600S
3	15/03/2021 04:20:00	⊞16:10	L	45	SMT1	15/03/2021 18:35:00	51300S
4	15/03/2021 18:35:00	⊞33:10	D	93	SMT1	16/03/2021 17:47:00	83520S
5		⊞7:10	C	116	SMT2	16/03/2021 17:47:00	83520S
6	16/03/2021 17:47:00	⊞40:10	U	120	SMT1	18/03/2021 04:27:00	124800S
7		⊞4:10	D	160	SMT2	18/03/2021 04:27:00	124800S
8	18/03/2021 04:27:00	⊞50:10	X	18	SMT1	18/03/2021 14:27:00	36000S
9		⊞51:10	Y	100	SMT2	18/03/2021 14:27:00	36000S
10	18/03/2021 14:27:00	⊞17:10	M	39	SMT1	19/03/2021 04:37:00	51000S
11		⊞30:10	A	85	SMT2	19/03/2021 04:37:00	51000S
12	19/03/2021 04:37:00	⊞28:10	C	0	SMT1	19/03/2021 06:16:00	5940S
13		⊞2:10	B	9	SMT2	19/03/2021 06:16:00	5940S
14	19/03/2021 06:16:00	⊞15:10	K	18	SMT1	19/03/2021 13:21:00	25500S
15		⊞52:10	Z	85	SMT2	19/03/2021 13:21:00	25500S
16	19/03/2021 13:21:00	⊞29:10	D	10	SMT1	19/03/2021 15:51:00	9000S
17		⊞47:10	U	15	SMT2	19/03/2021 15:51:00	9000S
18	19/03/2021 15:51:00	⊞20:10	A	34	SMT1	19/03/2021 21:31:00	20400S
19		⊞31:10	B	18	SMT2	19/03/2021 21:31:00	20400S
20	19/03/2021 21:31:00	⊞24:10	E	2	SMT1	19/03/2021 21:59:00	1680S
21	19/03/2021 21:59:00	⊞35:10	P	4	SMT1	19/03/2021 22:59:00	3600S
22	19/03/2021 22:59:00	⊞14:10	J	2	SMT1	19/03/2021 23:37:00	2280S
23	22/03/2021 00:00:00	⊞18:10	N	78	SMT1	22/03/2021 23:44:00	85440S
24		⊞19:10	O	89	SMT2	22/03/2021 23:44:00	85440S
25	22/03/2021 23:44:00	⊞3:10	C	58	SMT1	23/03/2021 11:20:00	41760S
26		⊞8:10	D	48	SMT2	23/03/2021 11:20:00	41760S
27	23/03/2021 11:20:00	⊞5:10	A	99	SMT1	24/03/2021 03:50:00	59400S
28		⊞6:10	B	77	SMT2	24/03/2021 03:50:00	59400S
29	24/03/2021 03:50:00	⊞22:10	C	26	SMT1	24/03/2021 09:02:00	18720S
30		⊞23:10	D	13	SMT2	24/03/2021 09:02:00	18720S
31	24/03/2021 09:02:00	⊞34:10	E	54	SMT1	24/03/2021 21:38:00	45360S
32	24/03/2021 21:38:00	⊞41:10	V	68	SMT1	25/03/2021 09:54:00	44160S
33		⊞42:10	W	92	SMT2	25/03/2021 09:54:00	44160S
34	25/03/2021 09:54:00	⊞25:10	F	17	SMT1	25/03/2021 14:09:00	15300S
35	25/03/2021 14:09:00	⊞36:10	Q	27	SMT1	25/03/2021 20:27:00	22680S
36		⊞37:10	R	10	SMT2	25/03/2021 20:27:00	22680S
37	25/03/2021 20:27:00	⊞43:10	X	2	SMT1	25/03/2021 21:57:00	5400S
38		⊞44:10	Y	15	SMT2	25/03/2021 21:57:00	5400S
39	25/03/2021 21:57:00	⊞12:10	H	80	SMT1	26/03/2021 20:37:00	81600S
40		⊞26:10	A	114	SMT2	26/03/2021 20:37:00	81600S
41	26/03/2021 20:37:00	⊞46:10	T	10	SMT1	26/03/2021 22:27:00	6600S
42	29/03/2021 00:00:00	⊞9:10	E	111	SMT1	30/03/2021 01:54:00	93240S
43	30/03/2021 01:54:00	⊞10:10	F	54	SMT1	30/03/2021 15:24:00	48600S
44		⊞11:10	G	11	SMT2	30/03/2021 15:24:00	48600S
45	30/03/2021 15:24:00	⊞27:10	B	17	SMT1	30/03/2021 21:00:00	20160S
46		⊞32:10	C	28	SMT2	30/03/2021 21:00:00	20160S
47	30/03/2021 21:00:00	⊞45:10	Z	79	SMT1	31/03/2021 03:35:00	23700S
48	31/03/2021 03:35:00	⊞13:10	I	77	SMT1	01/04/2021 02:41:00	83160S
49	01/04/2021 02:41:00	⊞48:10	V	11	SMT1	01/04/2021 04:20:00	5940S
50	01/04/2021 04:20:00	⊞38:10	S	73	SMT1	02/04/2021 06:20:00	93600S
51		⊞49:10	W	195	SMT2	02/04/2021 06:20:00	93600S
52	02/04/2021 06:20:00	⊞39:10	T	80	SMT1	02/04/2021 21:00:00	52800S

Picture 4-16: Operation table (b)

Property	Value
4:10	4:10
Type	Operation
Master operation	Mounting
Process number	10
Main output item	D
Production quantity	160
Quantity fixed level	0
Time fixed flag	
Resource fixed flag	Unfixed
User specified quantity	
User specified quantity fixed level	
User specified setup time	
User specified production time	34H40M
User specified teardown time	
User specified EST	
User specified LET	
User specified main resource	
User specified operation group	4
User specified group type	Same start time
Starting order	

Picture 4-17: General properties of the operation (b)

In this state, the sample model could be considered as completed. However, there is one more option of how to set the production time.

4.4.2 Set the same production time – option B

The function "Set the production time" modifies the shorter operation's production time to the same value of the longer operation. Now it is suitable to state the other options when the production times are summed up and its sum is assigned to both operations in the pair. It allows more options for the real production system that comes out from this model.

Such command should be in the following form.

```
ME.Work_UProductionTime=SumIF('Order',
            TARGET.Operations.UGroup==ME.UGroup,
            TARGET.Operations.OperationProductionTime);
```

This function could be useful if the SMT machine can not process both rails simultaneously but alternately. That means that if it operates the first rail, the second rail waits and conversely. Most likely, this solution should be closer to the client's SMT machine.

The following pictures show the Operation table (see Picture 4-20) and the operations' general properties (see Picture 4-21), where the difference in the production time between this method and the previous chapter method is obvious. This difference is also viewed in the Gantt chart, where the operations recalculated by the second execute option are longer than in the first example (see Appendix no.3b). It is caused by the fact that the SMT machine cannot simultaneously process the dual rails, as described in the Specification of the client's assignment chapter. Even though the tact time for the pattern and the sheet was neglected, the production time for the case of one pattern on the one sheet is set correctly.

	Production start time	Code	Main outpu	Production qu	Main resource	Production end time	Production time
1	15/03/2021 00:00:00	⊞1:10	A	26	SMT1	15/03/2021 06:43:00	24180S
2		⊞21:10	B	13	SMT2	15/03/2021 06:43:00	24180S
3	15/03/2021 06:43:00	⊞16:10	L	45	SMT1	15/03/2021 20:58:00	51300S
4	15/03/2021 20:58:00	⊞33:10	D	93	SMT1	17/03/2021 16:19:00	156060S
5		⊞7:10	C	116	SMT2	17/03/2021 16:19:00	156060S
6	17/03/2021 16:19:00	⊞40:10	U	120	SMT1	19/03/2021 22:59:00	196800S
7		⊞4:10	D	160	SMT2	19/03/2021 22:59:00	196800S
8	19/03/2021 22:59:00	⊞24:10	E	2	SMT1	19/03/2021 23:27:00	1680S
9	22/03/2021 00:00:00	⊞50:10	X	18	SMT1	22/03/2021 12:06:00	43560S
10		⊞51:10	Y	100	SMT2	22/03/2021 12:06:00	43560S
11	22/03/2021 12:06:00	⊞17:10	M	39	SMT1	23/03/2021 13:58:00	93120S
12		⊞30:10	A	85	SMT2	23/03/2021 13:58:00	93120S
13	23/03/2021 13:58:00	⊞28:10	C	0	SMT1	23/03/2021 15:37:01	5941S
14		⊞2:10	B	9	SMT2	23/03/2021 15:37:01	5941S
15	23/03/2021 15:37:01	⊞15:10	K	18	SMT1	24/03/2021 04:42:01	47100S
16		⊞52:10	Z	85	SMT2	24/03/2021 04:42:01	47100S
17	24/03/2021 04:42:01	⊞18:10	N	78	SMT1	26/03/2021 02:32:01	165000S
18		⊞19:10	O	89	SMT2	26/03/2021 02:32:01	165000S
19	26/03/2021 02:32:01	⊞29:10	D	10	SMT1	26/03/2021 07:12:01	16800S
20		⊞47:10	U	15	SMT2	26/03/2021 07:12:01	16800S
21	26/03/2021 07:12:01	⊞20:10	A	34	SMT1	26/03/2021 16:10:01	32280S
22		⊞31:10	B	18	SMT2	26/03/2021 16:10:01	32280S
23	26/03/2021 16:10:01	⊞35:10	P	4	SMT1	26/03/2021 17:10:01	3600S
24	26/03/2021 17:10:01	⊞25:10	F	17	SMT1	26/03/2021 21:25:01	15300S
25	26/03/2021 21:25:01	⊞43:10	X	2	SMT1	26/03/2021 23:09:01	6240S
26		⊞44:10	Y	15	SMT2	26/03/2021 23:09:01	6240S
27	26/03/2021 23:09:01	⊞14:10	J	2	SMT1	26/03/2021 23:47:01	2280S
28	29/03/2021 00:00:00	⊞3:10	C	58	SMT1	29/03/2021 22:00:00	79200S
29		⊞8:10	D	48	SMT2	29/03/2021 22:00:00	79200S
30	29/03/2021 22:00:00	⊞5:10	A	99	SMT1	31/03/2021 04:37:00	110220S
31		⊞6:10	B	77	SMT2	31/03/2021 04:37:00	110220S
32	31/03/2021 04:37:00	⊞22:10	C	26	SMT1	31/03/2021 12:38:00	28860S
33		⊞23:10	D	13	SMT2	31/03/2021 12:38:00	28860S
34	31/03/2021 12:38:00	⊞34:10	E	54	SMT1	01/04/2021 01:14:00	45360S
35	01/04/2021 01:14:00	⊞41:10	V	68	SMT1	01/04/2021 23:42:00	80880S
36		⊞42:10	W	92	SMT2	01/04/2021 23:42:00	80880S
37	01/04/2021 23:42:00	⊞36:10	Q	27	SMT1	02/04/2021 08:10:00	30480S
38		⊞37:10	R	10	SMT2	02/04/2021 08:10:00	30480S
39	02/04/2021 08:10:00	⊞27:10	B	17	SMT1	02/04/2021 16:53:00	31380S
40		⊞32:10	C	28	SMT2	02/04/2021 16:53:00	31380S
41	02/04/2021 16:53:00	⊞45:10	Z	79	SMT1	02/04/2021 23:28:00	23700S
42	05/04/2021 00:00:00	⊞12:10	H	80	SMT1	06/04/2021 17:40:00	150000S
43		⊞26:10	A	114	SMT2	06/04/2021 17:40:00	150000S
44	06/04/2021 17:40:00	⊞9:10	E	111	SMT1	07/04/2021 19:34:00	93240S
45	07/04/2021 19:34:00	⊞10:10	F	54	SMT1	08/04/2021 12:00:00	59160S
46		⊞11:10	G	11	SMT2	08/04/2021 12:00:00	59160S
47	08/04/2021 12:00:00	⊞46:10	T	10	SMT1	08/04/2021 13:50:00	6600S
48	08/04/2021 13:50:00	⊞13:10	I	77	SMT1	09/04/2021 12:56:00	83160S
49	09/04/2021 12:56:00	⊞48:10	V	11	SMT1	09/04/2021 14:35:00	5940S
50	12/04/2021 00:00:00	⊞38:10	S	73	SMT1	13/04/2021 16:36:00	146160S
51		⊞49:10	W	195	SMT2	13/04/2021 16:36:00	146160S
52	13/04/2021 09:20:00	⊞39:10	T	80	SMT1	14/04/2021 00:00:00	52800S

Picture 4-18: Operation table (c)

Property	Value
⊟4:10	4:10
Type	Operation
➡Master operation	Mounting
Process number	10
➡Main output item	D
Production quantity	160
Quantity fixed level	0
Time fixed flag	☐
Resource fixed flag	Unfixed
User specified quantity	
User specified quantity fixed level	
User specified setup time	
User specified production time	54H40M
User specified teardown time	
User specified EST	
User specified LET	
User specified main resource	
➡User specified operation group	4
➡User specified group type	Same start time
Starting order	

Picture 4-19: General properties of the operation (c)

4.5 Evaluation of the sample model results

After the reschedule mentioned above, the modeling process is completed, and it is suitable to evaluate the whole process according to the original model guideline.

Original Guideline and its fulfillment

- Create sample data for the simulation. ✓
  ⇒ Data was created for the 52 orders with the simple mounting processes, including 26 items with its model mix (see Appendix no. 2).

- Automate the data import to the Asprova APS. ✓
  ⇒ The CData software automatically executed the data import.

- Set the necessary parameters for further commands. ✓
  ⇒ All necessary parameters in the Asprova interface were set correctly.

- Create the function that executes the assignment between the orders according to the model mix. ✓
  ⇒ The assignment was executed by the created function "Assign into the pair".

- Modify the operation's production time. ✓
  ⇒ The operation's production time was modified by the created function "Set the same production time".

- Execute the schedule and evaluate the model results. ✓
  ⇒ The schedule's execution proceeded correctly without any error messages and could be presented to the client for further clarification.

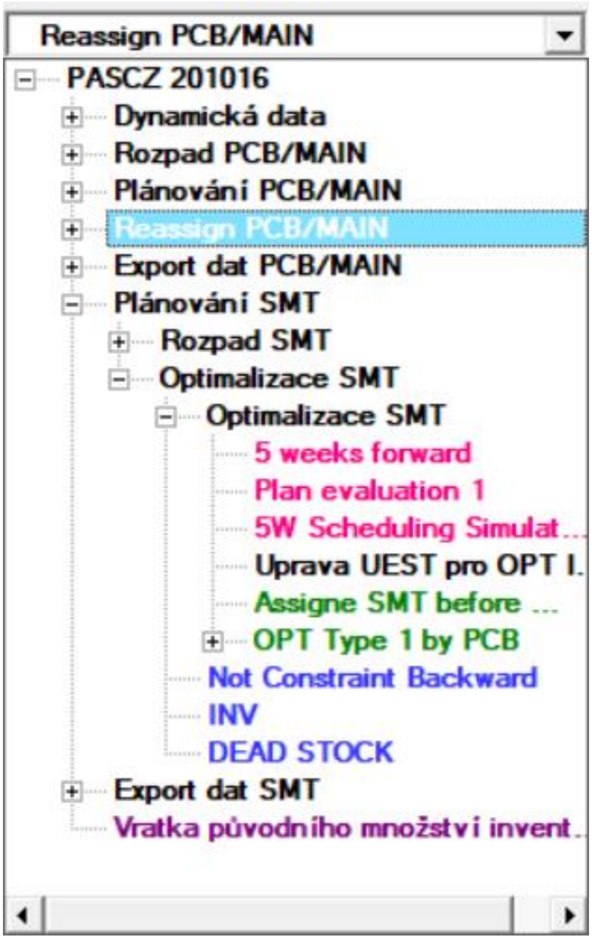
5 Application of model simulation solutions to a productive system

As was the model guideline fulfilled, the simulation based on the client's productive system has to proceed as the next project step. This simulation uses the real data from the client's systems outside of the whole production system. It allows enough space for the eventual additional modification in the algorithm without endangering production.

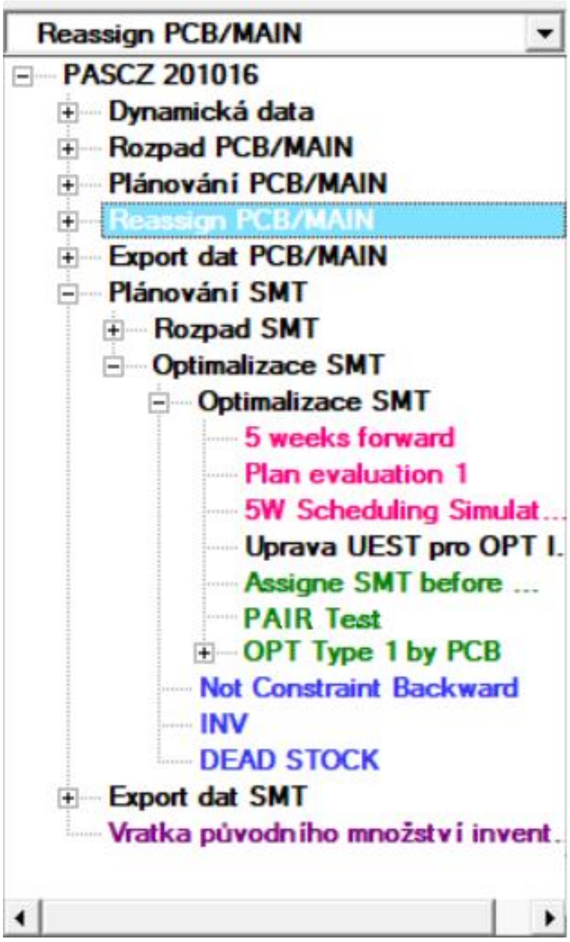
5.1 Client system

5.1.1 Command tree

As viewed in the command tree (see Picture 5-1), there are already several optimization commands. These commands were developed in the past for other line optimization in APS.



Picture 5-2: Original command tree

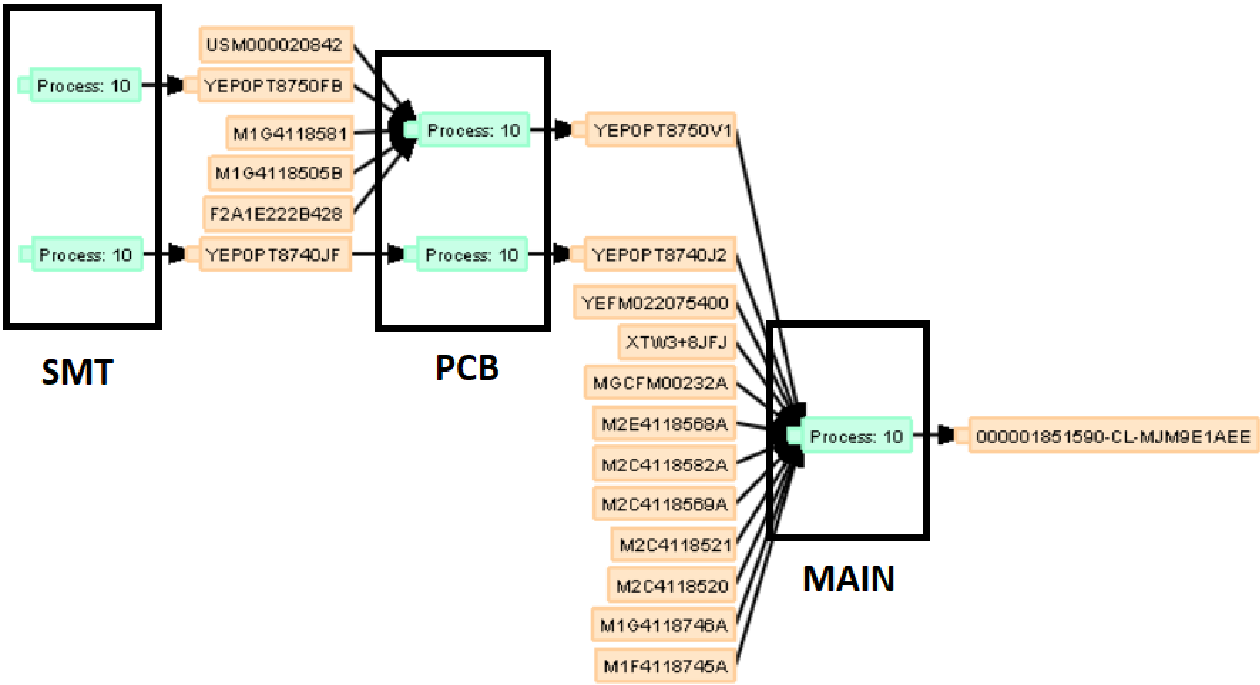


Picture 5-1: Modified command tree

Its content is not essential at this moment, but the order of the commands is. Commands are executed in descending order, so the dual rails SMT line optimization algorithm must be inserted into the commands carefully for further smooth scheduling. In this case, the algorithm (PAIR Test) from the model simulation will be inserted into the middle of the green zone. It means after the "Assigne SMT before..." and before the "OPT Type 1 by PCB" (see Picture 5-2).

5.1.2 Process flow

The whole client's manufacturing process is divided into three processes: SMT, PCB, and Mainline (see Picture 5-3), as is also displayed in detail in the appendix (see Appendix no. 4).



Picture 5-3: Process flow

SMT process

The SMT part of the process flow contains the whole SMD mounting process by the automatic SMT on the PCBs. It is necessary to incorporate the developed pairing algorithm right into this process. From the process flow it is evident that the SMT products could be produced on several SMT lines. The dual rail line (SMT08_1;2) is considered as two independent sources (not as one with two sources) that influence each other in the same way as was considered in the model simulation.

PCB process

Although the PCB process also includes the SMD mounting on the PCB, it contains more advanced operations for the more complex compositions. It means that these PCB processes use manual and semiautomatic operations, which are too complex for the fully automatic SMT line. The new algorithm does not influence these processes.

Mainline process

The last process stage is the Mainline that mounts all manufactured or purchased parts into the final products. As in the PCB process case, the new algorithm also does not influence the Mainline process.

5.1.3 Model solution implementation

The client's data were imported into the APS system in the same way as in the model simulation through the CData software. Although the SAP system data had to be modified for the algorithm, the whole uploading process proceeded correctly. This data contains, for example, 52 800 orders, and the BOM includes 847 000 rows. Compared to the model, it is about one thousand times more data. However, no errors appear.

After the reschedule, the Gant chart was generated (see Appendix no. 5). Many operations are planned after the deadline due to the simulation with the old data. However, the algorithm's test neglects this fact because it does not influence the simulation result. The dual-rail SMT line is also viewed as two independent sources (SMT08_1;2) with their original schedule. This original schedule has to be modified (by the algorithm) to schedule pairs that can be produced simultaneously with the correctly modified production time.

The algorithm was executed without any error messages (see Appendix no. 6) and fulfilled the client's expectations. Production pairs are made according to the items model mix, and the production time of both processes is equal to the sum of their original production time.

5.1.4 Material flow

The material flow (see Appendix no. 7) shows the manufacturing process (material flow) from the SMT line through the rest of the workstations to the mainline and the completed products. It means that the material flow is viewed in descending order, so the items, which are upper in the table, are part of the items that are lower in the table. The number of the required input parts by the lower items is covered by the viewed previous production and by the stock.

Further, it is suitable to explain why the material flow does not follow smoothly and is spread out in time. It is caused by the capacity of the sources, as is displayed in the appendix (see Appendix no. 8). Sources are processing more than this one order, so the orders have to be ordered by the priority. It follows that the APS Asprova system calculates the capacity of each source at every level of the schedule.

The due dates (red triangles) are also neglected because they do not influence the simulation results.

5.2 Algorithm deployment and the real data test evaluation

Thanks to the successful test, the algorithm can be deployed into real manufacturing operations. However, more factors tie to the implementation into the live production environment, such as the production settings or licenses. Due to these factors, the whole deployment process is highly time-consuming and will be processed after this Master's thesis deadline.

Despite the algorithm deployment's impossibility until the Master's thesis deadline, the simulations' results are satisfying. The project fulfilled each milestone from the assignment point of view, and the algorithm is ready to be used further.

6 Speculative calculation of the return on investment

Although the project fulfills all client's requirements, the main factor for further use is its return on investment. The primary project benefits which the client expects are the following.

- Increase of the line effectiveness
- The scheduled tact time equal to the real tact time
- Planner time savings 30 minutes per day
- Flexible MRP plan
- Automatic changes in both line trails simultaneously
- Visualization of the real material consumption
- Elimination of the non-Asprova manual changes in the schedule

All mentioned factors should be monetized for further financial analysis. This speculative calculation of the return on investment does not show the exact amounts due to the client's reasons. However, the mentioned calculation could be presented as a result in the percentage form.

6.1 Financial impacts of the project

Labor cost savings

The calculation formula follows.

- Daily working hourly rate = 8 hours
- Numbers of the planners = one planner
- Planner time savings = 30 minutes per day
- Planner time savings = (30/(8*60))*100 = 6,25 %

The time savings point shows that the planner time savings is equal to 6,25 % of the planner labor cost.

- Super gross wage (monthly) = X_1 [EUR]
- Energy and the corporate facilities cost = 30% from the Super gross wage
- Total cost:
  $Y_1 = X_1+0,3*X_1$ [EUR]
- Cost savings:
  $S_1 = Y_1*0,0625$ [EUR]

There are also other labor savings due to the increase of the line effectiveness. Smoother line operation leads to the time savings of the operators by 1,5 %. The calculation follows.

- Daily working hourly rate = 8 hours
- Numbers of the operators = eight operators
- Operator time savings = 7,2 minutes per day
- Operator time savings [%] = (7,2/(8*60))*100 = 1,5 %

- Super gross wage (monthly) = X_2 [EUR]
- Energy and the corporate facilities cost = included in the hourly machine rate
- Total cost:
  $Y_2 = 8*X_2$ [EUR]
- Cost savings:
  $S_2 = Y_2*0,015$ [EUR]

Savings by the line effectiveness

As was mentioned above, the calculation also involves the hourly machine rate. Due to eliminating the idle time (shortage of material, waiting between orders, unnecessary technical labor) caused by higher effectiveness of the line, there are time savings equal to 0,5 %. The calculation follows.

- Time savings = 0,5%
- Hourly machine rate = X_3 [EUR]
- Cost savings:
  $S_3 = X_3*0,005$ [EUR]

Savings by the reduction of the tied-up capital

The flexible MRP plan with equal scheduled and real tact time reduces the tied-up capital in the material. These savings were estimated to 0,2 % and so could be used for the more effective investments by the client's company. The mentioned calculation follows.

- Savings by the reduction of the tied-up capital = 0,2 %
- Purchased material on stock = X_4 [EUR]
- Work in progress = Y_4 [EUR]
- Finished products on stock = Z_4 [EUR]
- Total tied-up capital = SUM (X_4, Y_4, Z_4)
- Cost savings:
  $S_4 = 0,002*SUM (X_4, Y_4, Z_4)$

Savings by the pallet position

The exact schedule could also achieve space savings by the more accurate structure of the pallets with the SMD reels next to the SMT line. Although this point is more speculative than already mentioned points and will be neglect, it is appropriate to mention that.

- Number of saved pallet position = X_5
- One pallet position cost = Y_5
- Cost savings:
  $S_5 = X_5*Y_5$

Data security and storage

Until now, we were discussing only savings in this speculative calculation. However, more data that the client gets from this project requires additional data storage and a certain level of security. These requirements could be fulfilled by the in-house data centers or by outsourcing.

Cost of the data storage and security = E_6

6.2 Return on investment / Payback period

The Return on investment (ROI) indicator calculates whether the client is getting more money back than he is putting into the project. It is one of the most common profitability indicators that shows the investment effectivity in the percent so that the investor could get a simple overview of the whole project from the financial site.[38]

The calculation needs to evaluate the value of the gained amount from the project and the required investment. The investment is the client company's payment to the co-researcher company, and the gained amount is calculated as a difference between the savings and the additional costs. It follows that the gained amount is an income that investment has generated, and the investment is the total amount spent on investment.

Gained amount: $A_{G.}$

$A_G = S_1 + S_2 + S_3 + S_4$ - E_6 [EUR]

Amount spent: A_S

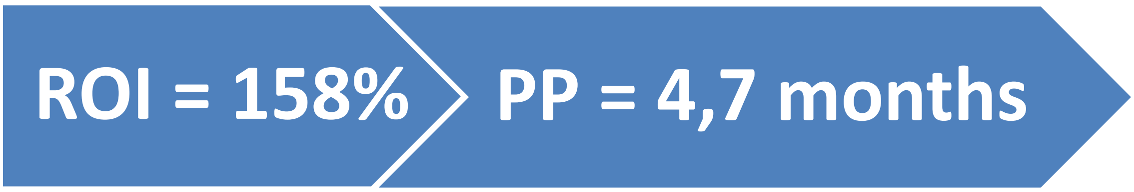
Annually return on investment: ROI

$$ROI = \left(\frac{A_G - A_S}{A_S}\right) * 100 = 158\%$$

Further, if the spent amount and the gained amount are put into the ratio, the payback period (PP) of the investment comes out.

Payback period: PP

$$PP = \frac{A_S}{A_G} = 4{,}7 \text{ months}$$



Conclusion

This Master's thesis is aimed to develop the algorithm in the APS system for the client's new SMT dual rail line. For this purpose, the thesis firstly states the development of the planning systems (MRP, MRPII, ERP, APS) with their theoretical description and benefits. Further, the introduction of the client company, co-researcher company, and the SMT technology follow together with the description of the Asprova APS system (license was provided by co-researcher company). By this description, the theoretical part of the thesis was complete.

The practical part of the thesis followed up with the development of the algorithm (designed in the Asprova interface). According to the specific items model mix, the client required the algorithm for order pairing and production time modification. Therefore, the created model data, including 52 orders, was uploaded into the APS system automatically through the CData software. The model algorithm was divided into two functions. Firstly, it modified the orders, and secondly, the operations. The whole model simulation was proceeded correctly and could be implemented into the client's real production data.

The implementation into the client's system could be simulated only on the client's data but not on the real production system due to the client deployment term. It is later than the Master's thesis deadline. However, there are no expected issues during the deployment since implementing the model results into the client's real data proceeded without errors.

The thesis benefits as time savings, increase of the line effectiveness, reduction of tied-up capital were described in detail in the last chapter. According to that was rated the speculative calculation of the return on investment and the payback period. Its result showed that the client got back the invested amount during the 4,7 months, and the annual ROI is equal to 158%.

Bibliography

[1] Not Just for Manufacturing, Material Requirements Planning (MRP) Is Indispensable for Any Business. *Smartsheet* [online]. smartsheet, c2020 [cit. 2020-10-30]. Dostupné z: https://www.smartsheet.com/guide-to-material-requirements-planning

[2] ROSER, Christoph. The (True) Difference Between Push and Pull. *Allaboutlean* [online]. allaboutlean, 2015 [cit. 2020-10-30]. Dostupné z: https://www.allaboutlean.com/push-pull/

[3] MRP vector illustration. Labeled material requirements planning system. In: *Dreamstime* [online]. dreamstime, c2000-2020 [cit. 2020-10-30]. Dostupné z: https://www.dreamstime.com/mrp-vector-illustration-labeled-material-requirements-planning-system-outlined-stock-inventory-demand-control-explained-resource-image141056612

[4] KENTON, Will. Material Requirements Planning (MRP). *Investopedia* [online]. Investopedia, 2020 [cit. 2020-11-01]. Dostupné z: https://www.investopedia.com/terms/m/mrp.asp

[5] Material Requirements Planning (MRP). *Inc.* [online]. Inc., 2020 [cit. 2020-11-02]. Dostupné z: https://www.inc.com/encyclopedia/material-requirements-planning-mrp.html

[6] Manufacturing Resource Planning Definition. *Investopedia* [online]. Investopedia, 2020 [cit. 2020-11-02]. Dostupné z: https://www.investopedia.com/terms/m/manufacturing-resource-planning.asp

[7] Enterprise Resource Planning and ERP Systems. *Simplilearn* [online]. simplilearn, 2015 [cit. 2020-11-02]. Dostupné z: https://www.simplilearn.com/erp-planning-and-erp-systems-rar102-article

[8] Enterprise Resource Planning (ERP). *Investopedia* [online]. Investopedia, 2020 [cit. 2020-11-30]. Dostupné z: https://www.investopedia.com/terms/e/erp.asp

[9] Co je ERP? *Oracle* [online]. Oracle, c2020 [cit. 2020-11-03]. Dostupné z: https://www.oracle.com/cz/erp/what-is-erp/

[10] Introduction to Planning and Scheduling. *Engineering management* [online]. Engineering management, c2020 [cit. 2020-11-04]. Dostupné z: https://www.engineeringmanagement.info/2019/01/introduction-to-planning-and-scheduling.html

[11] Plánování a rozvrhování výroby APS. *Karat* [online]. Karat, c2006-2020 [cit. 2020-11-04]. Dostupné z: https://www.karatsoftware.cz/erp-karat/funkcionality/planovanie-rozvrhovanie-vyroby-aps

[12] SODOMKA, Petr. Pokročilé plánování a řízení výroby. *System online* [online]. System online, 2011 [cit. 2020-11-05]. Dostupné z: https://www.systemonline.cz/rizeni-vyroby/pokrocile-planovani-a-rizeni-vyroby.htm

[13] HÉGR, Michael. APS systém nenahradí funkcionalitu ERP systému. *System online* [online]. 2010: System online [cit. 2020-11-05]. Dostupné z: https://www.systemonline.cz/rizeni-vyroby/aps-system-nenahradi-funkcionalitu-erp-systemu.htm

[14] Your Lean Manufacturing Solution Asprova. *Asprova* [online]. Asprova [cit. 2020-11-08]. Dostupné z: https://www.asprova.com/en/

[15] Visual Management. *Asprova* [online]. Asprova [cit. 2020-11-08]. Dostupné z: https://www.asprova.com/en/asprova/modules/visual_management.html

[16] Inventory Reduction. *Asprova* [online]. Asprova [cit. 2020-11-10]. Dostupné z: https://www.asprova.com/en/asprova/modules/inventory_reduction.html

[17] Production Lead Time Reduction. *Asprova* [online]. Asprova [cit. 2020-11-10]. Dostupné z: https://www.asprova.com/en/asprova/modules/lead_time_reduction.html

[18] Asprova MES. *Asprova* [online]. Asprova [cit. 2020-11-11]. Dostupné z: https://www.asprova.com/en/asprova/modules/asprova_mes.html

[19] Asprova BOM. *Asprova* [online]. Asprova [cit. 2020-11-11]. Dostupné z: https://www.asprova.com/en/asprova/modules/asprova_bom.html

[20] Asprova SED. *Asprova* [online]. Asprova [cit. 2020-11-11]. Dostupné z: https://www.asprova.com/en/asprova/modules/asprova_schedule-editor.html

[21] Asprova MRP. *Asprova* [online]. Asprova [cit. 2020-11-11]. Dostupné z: https://www.asprova.com/en/asprova/modules/asprova_ls_asprova_mrp.html

[22] Asprova MS. *Asprova* [online]. Asprova [cit. 2020-11-11]. Dostupné z: https://www.asprova.com/en/asprova/modules/asprova_ms.html

[23] Asprova APS. *Asprova* [online]. Asprova [cit. 2020-11-11]. Dostupné z: https://www.asprova.com/en/asprova/modules/asprova_ap.html

[24] Module Feature Table. *Asprova* [online]. Asprova [cit. 2020-11-11]. Dostupné z: https://www.asprova.com/en/asprova/modules/module_feature_table.html

[25] Asprova NLS / Asprova DS. *Asprova* [online]. Asprova [cit. 2020-11-11]. Dostupné z: https://www.asprova.com/en/asprova/modules/asprova_nls_asprova_ds.html

[26] Network Modules. *Asprova* [online]. Asprova [cit. 2020-11-15]. Dostupné z: https://asprova.net/2014/09/15/network-modules/

[27] How does SMT electronics assembly work? *ESO-electronic* [online]. ESO-electronic, 2014 [cit. 2020-11-15]. Dostupné z: https://www.eso-electronic.com/en/knowledge-base/manufacturing/how-does-smt-electronics-assembly-work/

[28] The PCB Assembly Process. *PCB Way* [online]. PCB Way, 2018 [cit. 2020-11-17]. Dostupné z: https://www.pcbway.com/blog/PCB_Assembly/The_PCB_Assembly_Process.html

[29] Pokročilé plánování výroby. *Aimtec* [online]. Plzeň: Aimtec [cit. 2020-11-20]. Dostupné z: https://www.aimtecglobal.com/advanced-planning-and-scheduling/

[30] Asprova scheduling software Resellers. *Asprova* [online]. Asprova [cit. 2020-11-20]. Dostupné z: https://www.asprova.com/en/distributor/asprova_resellers.html

[31] Automotive PCB: The Chassis of the Modern Automotive Industry. *Sierra circuits* [online]. 2019 [cit. 2021-5-21]. Dostupné z: https://www.protoexpress.com/blog/automotive-pcb-chassis-modern-automotive-industry/

[32] SMT Engineer: How to Become an SMT Process Engineer. *OurPCB* [online]. [cit. 2021-5-21]. Dostupné z: https://www.ourpcb.com/smt-engineer.html

[33] What is the Difference between Planning and Scheduling? *DemandCaster* [online]. DemandCaster, 2018 [cit. 2020-11-23]. Dostupné z: https://www.demandcaster.com/blog-news/what-is-the-difference-between-planning-and-scheduling/

[34] MRP, ERP, SCM AND APS SOFTWARE SOLUTIONS: DIFFERENT BUT COMPLEMENTARY (II). *Blue smart* [online]. Espinardo (Murcia): Blue smart [cit. 2020-11-24]. Dostupné z: http://blue-smart.es/en/software-mrp-erp-scm-and-aps-software-solutions-differences/

[35] Automotive PCB. *Venture electronics* [online]. Venture electronics, c2007-2019 [cit. 2020-11-24]. Dostupné z: https://www.venture-mfg.com/automotive-pcb-capabilities/

[36] NPM-TT2 Twin Tray Assembly Platform. *Panasonic* [online]. Panasonic, c2020 [cit. 2020-11-25]. Dostupné z: https://www.panasonicfa.com/content/npm-tt-twin-tray-assembly-platform

[37] SMT LINE The Ultimate Guide. *Talk electronics* [online]. Talk electronics, c2000-2020 [cit. 2020-11-25]. Dostupné z: https://electronicstalk.com/smt-line/

[38] SEO Tips. *SEO BOX* [online]. Brisbane, 2017 [cit. 2021-5-12]. Dostupné z: https://www.seobox.com.au/why-seo-has-the-best-roi/

List of appendices

Appendices

Appendix no. 1: SMT dual-line case example [37]

SMT dual-line case example

1) Loader

2) Solder paste printing

3) Check the PCB printing quality

4) NG buffer

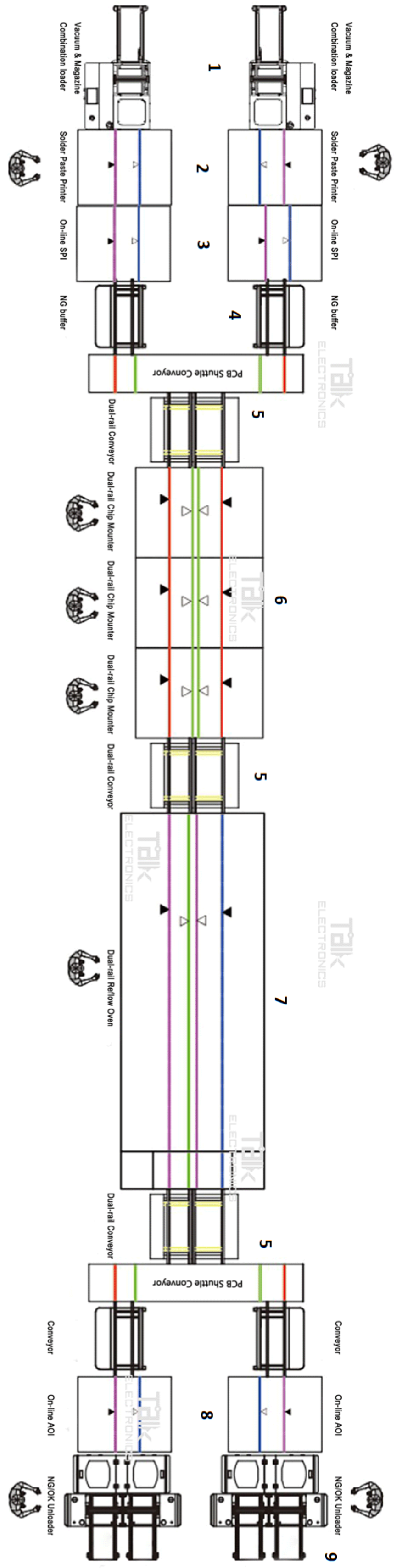
5) Conveyor

6) Placement machines

7) Reflow Owen

8) Check the PCB quality

9) Unloader



Appendix no. 2: Sample model input data

- **Order table**

OrderCode	Item	Qty	DueDate	OrderCode	Item	Qty	DueDate
01	A	26	2021/05/01 00:00:00	27	B	17	2021/05/10 00:00:00
02	B	9	2021/05/02 00:00:00	28	C	0	2021/05/11 00:00:00
03	C	58	2021/05/03 00:00:00	29	D	10	2021/05/03 00:00:00
04	D	160	2021/05/04 00:00:00	30	A	85	2021/05/13 00:00:00
05	A	99	2021/05/05 00:00:00	31	B	18	2021/05/14 00:00:00
06	B	77	2021/05/06 00:00:00	32	C	28	2021/05/15 00:00:00
07	C	116	2021/05/07 00:00:00	33	D	93	2021/05/01 00:00:00
08	D	48	2021/05/08 00:00:00	34	E	54	2021/05/06 00:00:00
09	E	111	2021/05/09 00:00:00	35	P	4	2021/05/07 00:00:00
10	F	54	2021/05/10 00:00:00	36	Q	27	2021/05/08 00:00:00
11	G	11	2021/05/11 00:00:00	37	R	10	2021/05/13 00:00:00
12	H	80	2021/05/12 00:00:00	38	S	73	2021/05/14 00:00:00
13	I	77	2021/05/13 00:00:00	39	T	80	2021/05/15 00:00:00
14	J	2	2021/05/14 00:00:00	40	U	120	2021/05/01 00:00:00
15	K	18	2021/05/15 00:00:00	41	V	68	2021/05/06 00:00:00
16	L	45	2021/05/01 00:00:00	42	W	92	2021/05/07 00:00:00
17	M	39	2021/05/02 00:00:00	43	X	2	2021/05/08 00:00:00
18	N	78	2021/05/03 00:00:00	44	Y	15	2021/05/09 00:00:00
19	O	89	2021/05/04 00:00:00	45	Z	79	2021/05/10 00:00:00
20	A	34	2021/05/05 00:00:00	46	T	10	2021/05/11 00:00:00
21	B	13	2021/05/06 00:00:00	47	U	15	2021/05/12 00:00:00
22	C	26	2021/05/07 00:00:00	48	V	11	2021/05/13 00:00:00
23	D	13	2021/05/06 00:00:00	49	W	195	2021/05/14 00:00:00
24	E	2	2021/05/07 00:00:00	50	X	18	2021/05/15 00:00:00
25	F	17	2021/05/08 00:00:00	51	Y	100	2021/05/01 00:00:00
26	A	114	2021/05/09 00:00:00	52	Z	85	2021/05/02 00:00:00

- **Integrated master editor table**

FinalItem	ProcesNumber	ProcessCode	InstructionType	Resource/Item	ProductionTime
A	10	Mounting	I	A-Material	
A	10	Mounting	U	SMT	11mp
B	10	Mounting	I	B-Material	
B	10	Mounting	U	SMT	12mp
C	10	Mounting	I	C-Material	
C	10	Mounting	U	SMT	13mp
D	10	Mounting	I	D-Material	
D	10	Mounting	U	SMT	14mp
E	10	Mounting	I	E-Material	
E	10	Mounting	U	SMT	15mp
F	10	Mounting	I	F-Material	
F	10	Mounting	U	SMT	16mp
G	10	Mounting	I	G-Material	
G	10	Mounting	U	SMT	17mp
H	10	Mounting	I	H-Material	
H	10	Mounting	U	SMT	18mp
I	10	Mounting	I	I-Material	
I	10	Mounting	U	SMT	19mp
J	10	Mounting	I	J-Material	
J	10	Mounting	U	SMT	20mp
K	10	Mounting	I	K-Material	
K	10	Mounting	U	SMT	19mp
L	10	Mounting	I	L-Material	
L	10	Mounting	U	SMT	18mp
M	10	Mounting	I	M-Material	
M	10	Mounting	U	SMT	17mp
N	10	Mounting	I	N-Material	
N	10	Mounting	U	SMT	16mp
O	10	Mounting	I	O-Material	
O	10	Mounting	U	SMT	15mp
P	10	Mounting	I	P-Material	
P	10	Mounting	U	SMT	14mp
Q	10	Mounting	I	Q-Material	
Q	10	Mounting	U	SMT	13mp
R	10	Mounting	I	R-Material	
R	10	Mounting	U	SMT	12mp
S	10	Mounting	I	S-Material	
S	10	Mounting	U	SMT	11mp
T	10	Mounting	I	T-Material	
T	10	Mounting	U	SMT	10mp
U	10	Mounting	I	U-Material	
U	10	Mounting	U	SMT	9mp
V	10	Mounting	I	V-Material	

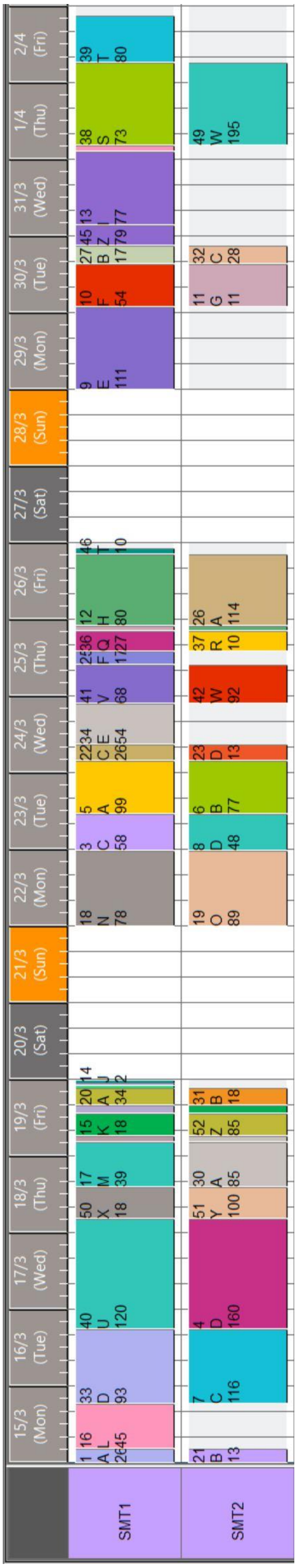
V	10	Mounting	U	SMT	8mp
W	10	Mounting	I	W-Material	
W	10	Mounting	U	SMT	7mp
X	10	Mounting	I	X-Material	
X	10	Mounting	U	SMT	6mp
Y	10	Mounting	I	Y-Material	
Y	10	Mounting	U	SMT	5mp
Z	10	Mounting	I	Z-Material	
Z	10	Mounting	U	SMT	5sp

- **Item table**

Item code	ModelMix
A	B;H;M
B	C;A;M
C	D;B
D	C;U
E	
F	G
G	F
H	I;A
I	H
J	K
K	J;Z
L	
M	A;B
N	O
O	N
P	R
Q	R
R	P;Q
S	U;W
T	
U	S;D
V	W
W	V;S
X	Y
Y	X
Z	K

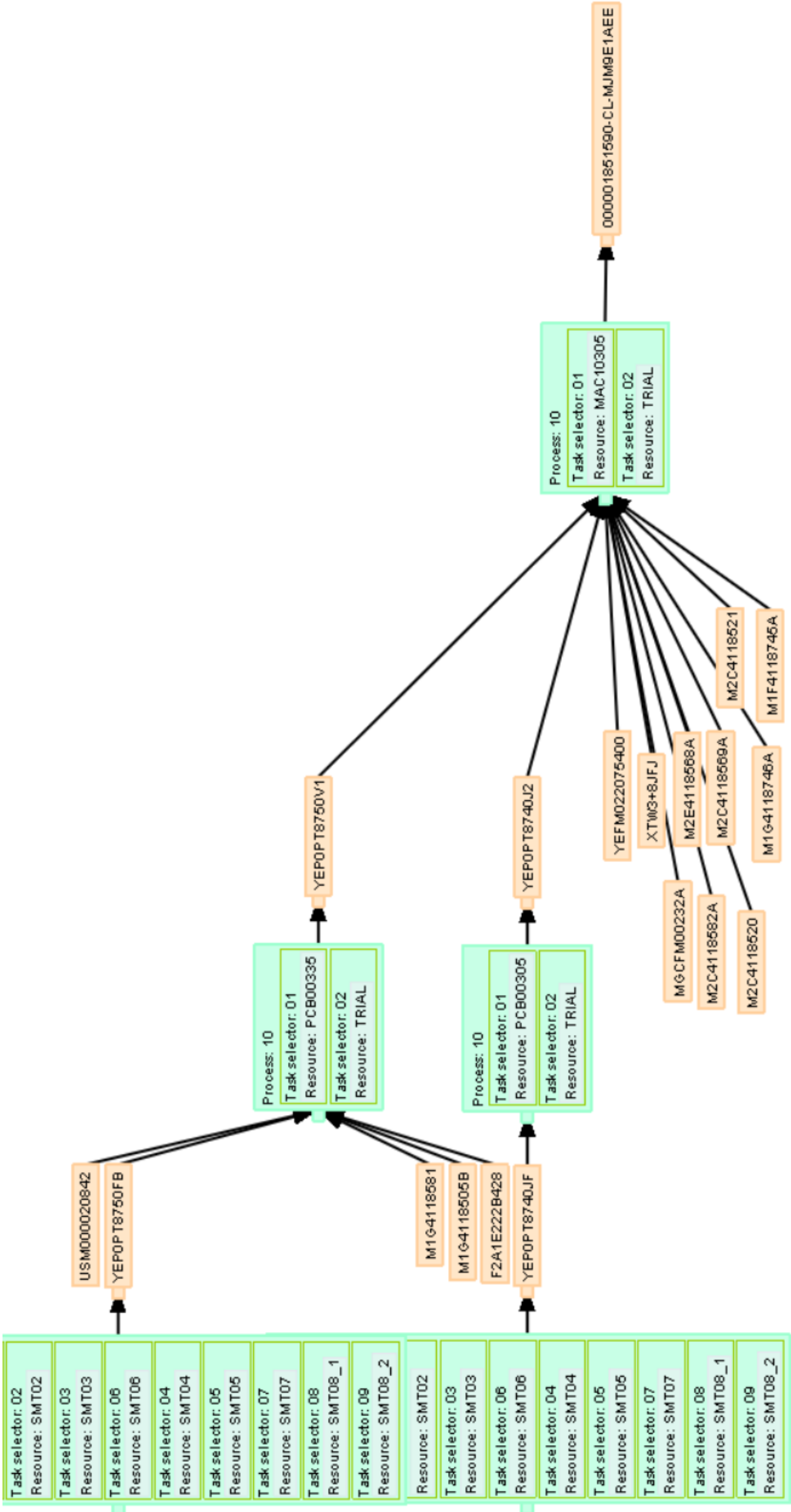
Appendix no. 3: Sample model - Gantt chart

(a)

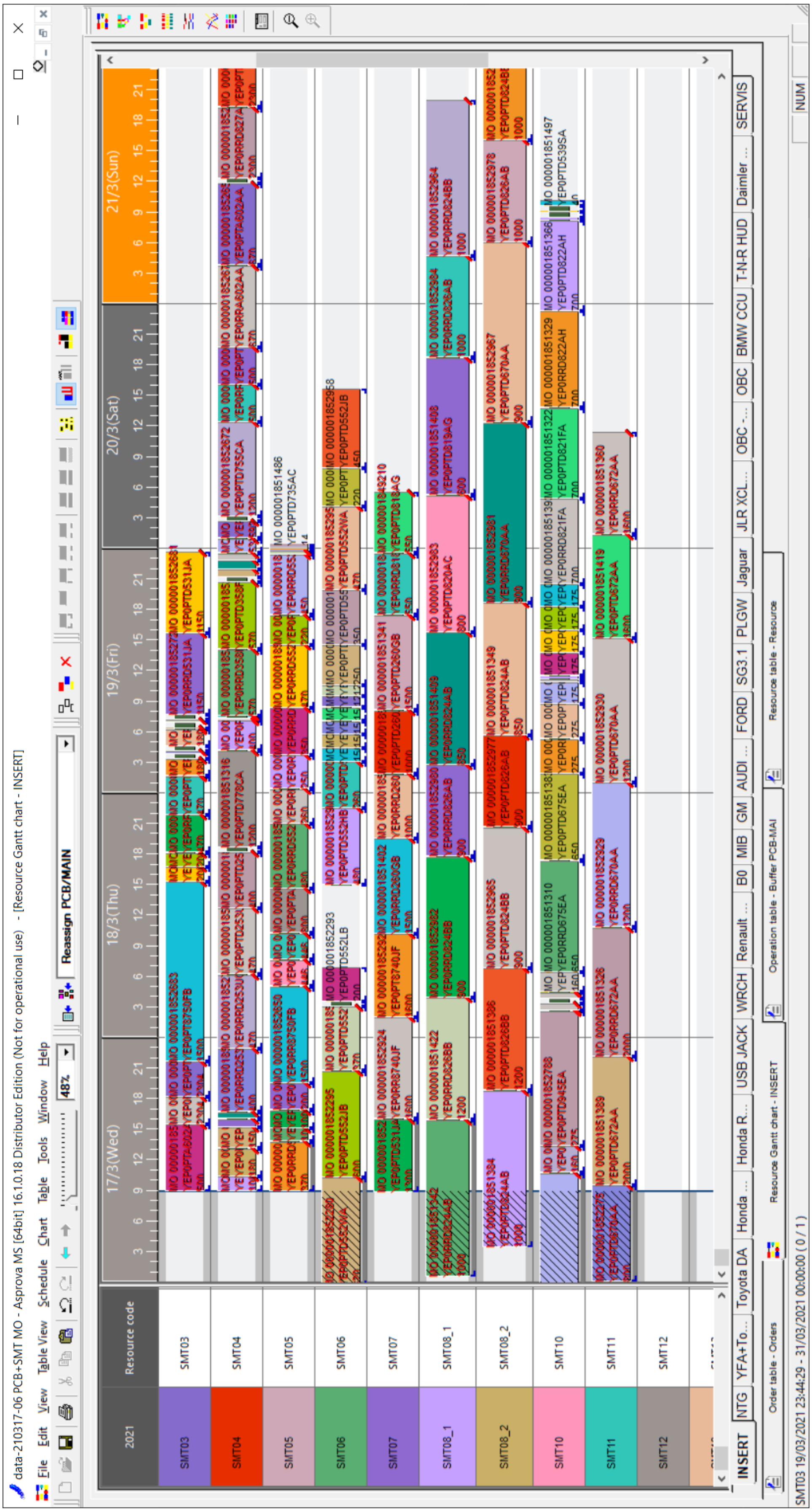


(b)

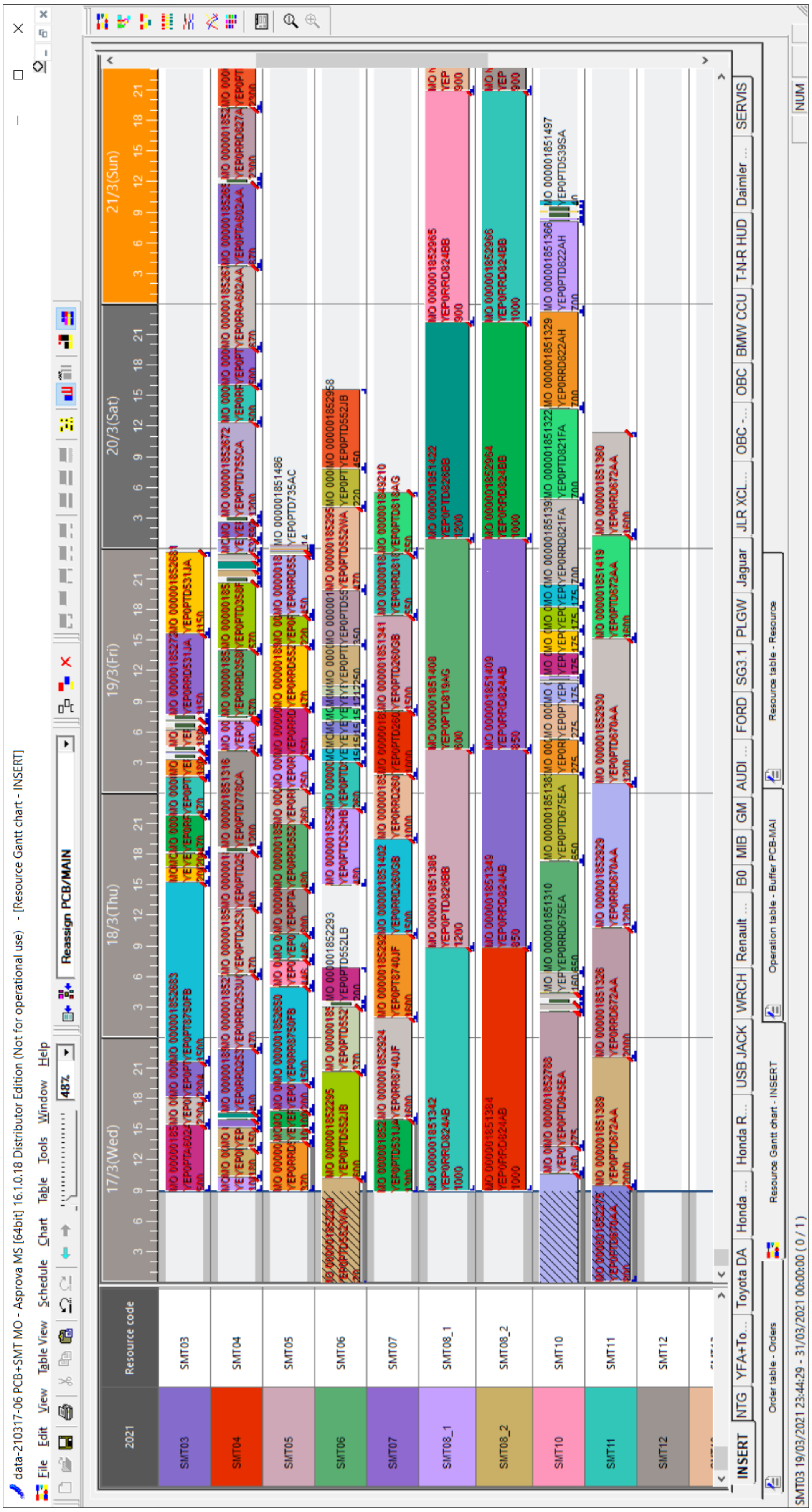
Appendix no. 4: Detailed Process flow



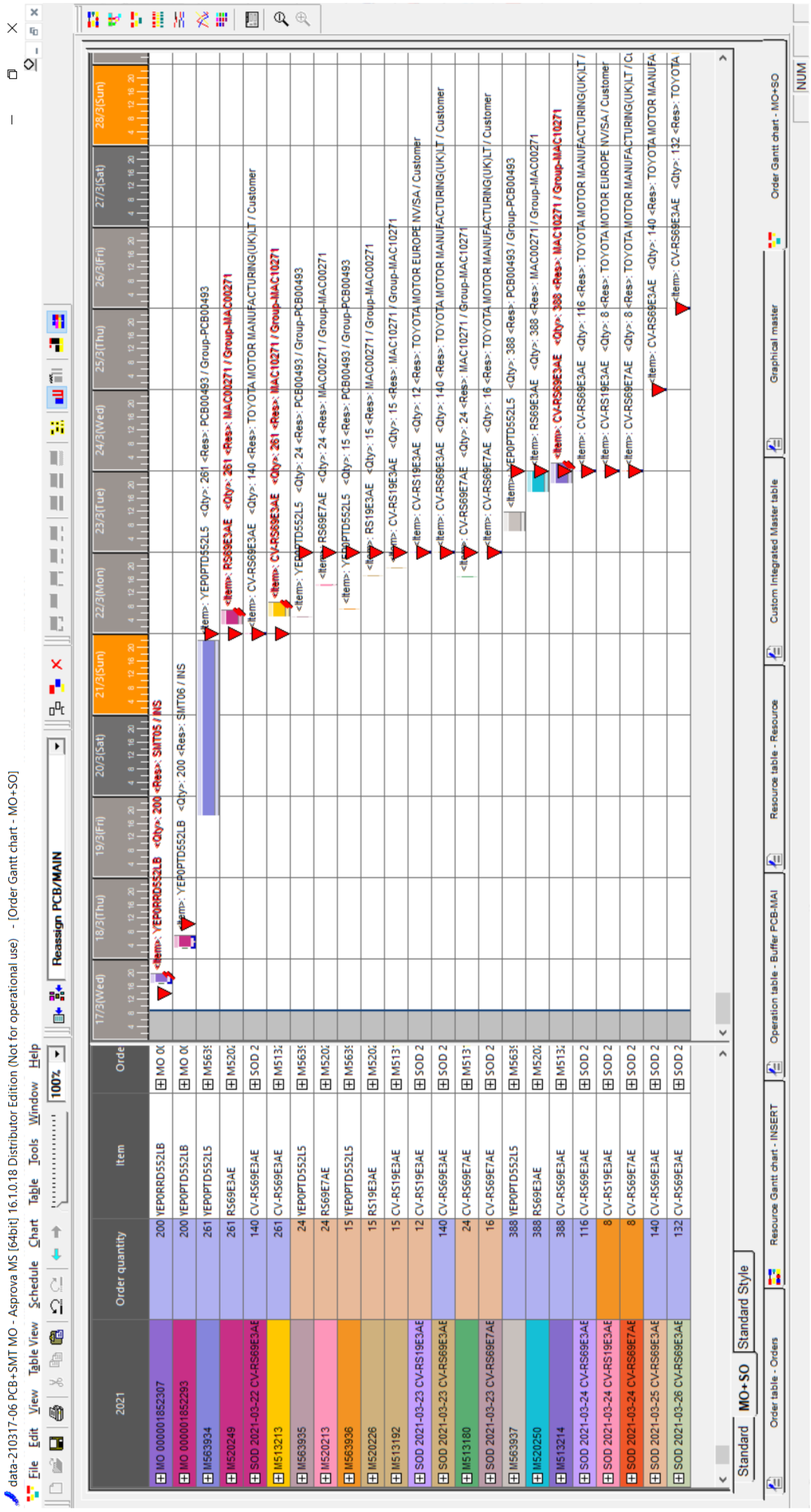
Appendix no. 5: Default Gantt chart



Appendix no. 6: Modified Gantt chart



Appendix no. 7: Material flow



Appendix no. 8: Material flow - source capacity