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Efficient and effective utilization of limited resources: Scheduling of MRI development test environment, a case study at Philips Healthcare

Master Thesis of Boyan Lazarov

Efficient and effective utilization of limited resources: Scheduling of MRI development test environment, a case study at Philips Healthcare

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Acknowledgements

First and foremost, I would like to thank my family and especially my parents Kameliya and Georgi. Without their support in the most difficult times and inspiration, I would not be able to even start my education in the Netherlands. Through good and bad they were always next to me and helping me in every way they could. Thank you, mom and dad! Then, there are my brother Petyr and my sister Maria who believed in me and encourage me in every possible moment.

My biggest thank is for my supervisors Klaas Sikkel and Ton Spil. I admire your patience and teaching skills. Thank you for all your advices and recommendations that you gave me. Thank you for standing behind my interests and continuously pushing me to the end! In addition, thank you Maya Daneva.

I would like to say thank you also to my supervisors from Philips – Ralph Horst and Theo van Roosmalen. I will never forget what experience that was. Thank you, Theo, for the hours and hours that we spent together talking and you teaching me how to see behind the lines.

I would like to thank also Ivelin Alexandrov, the person who I met first in the Netherlands and remain my dearest friend through the years. Thank you for sharing your house and food with me. I would like to thank also Milan Schramm and Tassos Papazoglou, my university colleagues who I met in my very first class. Thank you for all the good memories with you. I would like to mention also to mention Nelly, Iliana, Ivana, Nasko, Pavel, Marie, Johannes. Thank you all!

Boyan Lazarov

Sofia, 19 May 2016

Executive summary

Maximizing the effectiveness and efficiency of resource utilization has been always a challenge for the industry. Organizations strive to improve the planning and scheduling of their limited resource and respectfully to increase productivity at lower costs. In the settings of research and development pipeline for complex systems such as MRI, this becomes a real challenge. During the product realization process many unexpected events could cause deviation of the original plan. These could be equipment failure, under- or overestimation of processing time, new task arrival, delay or shortage of materials, shift in priority and many more.

The purpose of this master thesis was to find a solution for the resource allocation process of a development test environment. The three main objectives are first, to increase the resource utilization efficiency why maintaining or improving the current levels of effective utilization. Second, the scheduling process has to indicate future improvements on the decision making. Third, the solution has to provide flexibility in order to cope with uncertainty, but it should not significantly disturb schedule stability.

The academic literature classifies this challenge as resource constrained project scheduling under uncertainty. There are two main domains of research that focus on this problem. The first is concerned with the use of deterministic baseline schedule. If statistical information about possible disruptions is known, then proactive scheduling procedures are incorporated. Finally, reactive scheduling procedures could be invoked during execution of the project, in the case of schedule disruptions. The second domain is the stochastic scheduling, where instead of baseline schedule, tasks are scheduled based on a set of scheduling policies. The scheduling process continues during the execution of the project and it is considered as a multi-stage decision process.

During the initial research the main stakeholders were interviewed and from these interviews it became clear that stochastic scheduling is not a viable solution to the faced challenges at this moment of time. Therefore, the proposed solution is based on the hybrid strategy of predictive-reactive scheduling. The predictive part is the construction of deterministic baseline schedules that considers possible disturbance but does not take action on them. The predictive strategy is selected before the proactive one due the lack of sufficient historical data. In addition, it is easier to adapt by the stakeholders, since it is closer to the ordinary way of working. However, once enough data is gathered a proactive approach could further increase efficiency. The reactive part is a mandatory part independently from the selection of predictive or proactive approach.

The proposed solution increases the resource utilization efficiency by mainly removing waste from the scheduling process, by standardizing the roles and information on both tactical and operational level, and the baseline schedules, by introducing modified block scheduling strategy with two types of blocks – big (allocation blocks) and small blocks (scheduled task blocks). The unification of the information also contributes to the learning aspects of the process, while the modified blocks increase significantly the flexibility.

The solution was evaluated by the business stakeholders as improvement to the current situation. For future improvements it is recommended to build on towards a proactive strategy, which will reduce the decision making in the reactive part. In addition, an automation of the configuration management process will enable huge improvements towards the optimality of the scheduling process.

Abbreviations

BU	–	Business Unit
CTM	–	Coil Test Module
DMADV	–	Define Measure Analyze Design Verify
DTE	–	Development Test Environment
HW	–	Hardware
MR(I)	–	Magnetic Resonance, Magnetic Resonance Imaging
NPI	–	New Product Introduction
PMO	–	Project Management Office
PRP	–	Product Realization Process
R&D	–	Research and Development
(S)RCPSP	-	(Stochastic) Resource-Constrained Project Scheduling Problem
STM	–	Software Test Machine
SW	–	Software
TB	–	Test Bay
V&V	–	Verification & Validation

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1. Introduction

Resource allocation and task scheduling is a well-researched topic in the academic literature. Many researchers from different subject areas put lately a tremendous attention on scheduling, tripling the annual scientific publications compared to the beginning of the century. The vast majority of this work is in the area of operations research (e.g. manufacturing), computer science (e.g. computing and networks) and mathematics (theoretical), which handles mainly non-human resource, such as machines and signals, whereas project scheduling is concerned mainly with human resources. Nevertheless, all of them aim to develop an optimization model for optimal or suboptimal algorithms and procedures. An optimization model addresses "the necessary decisions made on the acquisition, utilization and allocation of resource to satisfy customer needs and requirements in the most efficient and effective way" (Graves, 1999).

A well-known problem in scheduling literature is the resource-constrained project scheduling (RCPSP) under uncertainty. For instance, new product development in healthcare sector is a highly regulated process. Each product must go through series of tests related mainly to safety, efficacy and environmental impact, in order to obtain certification (Choi, Realff, & Lee, 2007). Large amount of researchers put focus on optimizing development processes of chemical products in the agricultural and pharmaceutical industries (Verderame, Elia, Li, & Floudas, 2010). However, the development process of complex and expensive high-tech systems, such as diagnostic imaging systems, did not draw so much attention. An explanation for this could be the small number of MRI manufactures compared to the chemical industry. There are only three key big companies accounted for more than three-quarters of the world medical imaging market and they are General Electric, Philips and Siemens. This master thesis is conducted at Philips Healthcare at Best, Netherlands.

1.1 About Philips

1.1.1 Philips mission and strategy

Over 120 years Koninklijke Philips N.V., commonly known only as Philips, has been dedicated on its mission to improve people's live through meaningful innovations. The latest slogan "innovation and you" (2014) is the most simple and clear statement that symbolize the innovative and customer centric culture in the organization. Philips is a strong and trusted brand that was built through innovative solutions in lighting, consumer lifestyle and healthcare sectors that improved the quality of life of millions of people all over the world by making the world healthier and more sustainable.

1.1.2 Philips Healthcare structure

Philips Healthcare is organized around four strategic business groups ("Philips Annual Report 2013," 2014): Imaging Systems (38% of €9.6 billion total sales), Patient Care & Clinical Informatics (22%), Home Healthcare Solutions (14%), and Customer Services (26%). The focus of this research is on the Magnetic Resonance Imaging (MRI) business unit, which is part of Advanced Diagnostic Imaging, second on sales after interventional X-Ray (iXR) in Imaging Systems.

For MRI research and development (R&D) department work 300-500 employees and activities are spread in six locations over the world: Cleveland (USA), Latham (USA), Best (Netherlands), Helsinki (Finland), Bangalore (India), and Suzhou (China). Best is responsible for most of the verification and validation (V&V) activities, which are performed on testing systems. Therefore, in Best is located the biggest Development Test Environment (DTE) department that manages and supports the testing systems.

1.1.3 DTE department

Development Test Environment provides and supports space and equipment that could be used for testing purpose of new product introduction (NPI) projects and released projects (from the field), customer visits, photo-shoots, trainings, workshops and other activities. DTE organizational structure consists of two managers - group and project leaders, logistics team, and engineers' team, the latter is also called development support. The logistics team takes care for order and delivery of parts and equipment, while the development support maintains the testing systems.

The most expensive and scarce resource in the facility are the MRI systems, 17-20 simulated customer environments called Test Bays (TB), with total assets of more than €20 million. In addition, there are Software Test Machines (STMs), Coil Testing Modules (CTMs), Workbenches (WB), coils, phantoms and other equipment. Since the demand for test bays is bigger than the availability, a reservation process is established to handle time allocation requests. It is important to note that such a process is not clearly, nor completely defined and documented. The following section is a representation of the way of working obtained through interviews, existing documentation and observations.

1.1.4 DTE reservation process

The reservation process (see Figure 1-1) spreads among two domains – project management and DTE management. The process starts from the creation of the program plan where program managers allocate priorities and create a plan for the deliverables of the different projects. Based on the program plan, project managers create the projects plans, which vary depending on the type of the project. Next, each team creates a project testing plan where it allocates main test activities in time and priority. Since every project requires different system configurations and amount of test bays (see Chapter 3), projects plans are aligned with the DTE macro allocation board.

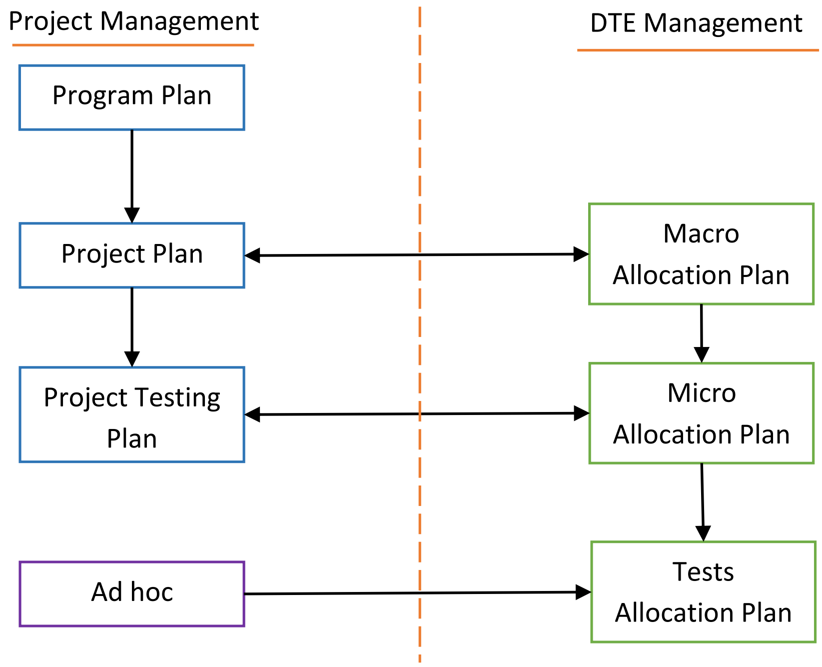


Figure 1-1. High level DTE reservation process (representation)

The macro allocation plan arranges test bays' system configuration in time according to projects' requirements and it also includes test bays' regularization (maintenance) planning. Based on the macro allocation plan and the project testing plan each project team creates a micro allocation plan where it specifies each test activity with concrete time and test bay. Next, the plan is incorporated in the tests allocation plan as reservations in the reservation system. Any ad hoc requests are directly addressed to the tests allocation plan in the reservation system.

1.2 Problem description

The problem from scientific point of view could be classified as resource-constrained multi-project scheduling under uncertainty in new product development (R&D environment/pipeline), for unifying notation, a model, a classification scheme, such as a resource environment, activity characteristics, and objective functions see (Brucker, Drexl, Möhring, Neumann, & Pesch, 1999).

The key motivators for initiating this project are the growing demand for resource time and the expanding system configuration diversity. While in the past couple of years there were no significant process-wise changes, TB utilization on average increased from 51% for 2013 to 66% for 2014 during work hours (see Appendix D: TBs utilization for 2013 and 2014). In addition, the increase in system configuration diversity, currently 13 unique out of 16 TB configurations, significantly limits the options in choosing a resource. These evidence clearly point out the limited resource environment of this case and the need of smart decision making in efficiently utilizing these resource.

A further contribution to the complexity of the case is its scale, mainly the simultaneously running multiple projects. Currently, more than ten R&D projects are taking place globally with the allocation of more than 300 employees. Since Philips has a matrix organization, human and non-human resources are shared between different projects. This leads to further cross-project alignment on multiple hierarchy levels.

Last but not least, the R&D environment self-assumes high level of uncertainty. Strict regulations by health agencies, such as FDA in USA, requires a series of tests to be performed, in addition to the regular technology performance tests. If these test are not satisfying, all activities could be stopped until the certain milestone is not met. Moreover, MRI scanners are very complex systems, which consist of many components, for a basic overview of hardware components (Rajan, 1998). The life expectancy of a system is 7-10 years, and hardware problems on different components occur often. Some failures could be very expensive, e.g. when a system's magnet field has to be turned off (off-field), the cooling gas (liquid helium) has to be released in the atmosphere. A refill of the cooling system could cost between €20 000 and €30 000.

Currently DTE's reservation process, in particular the DTE reservation system, is at the end of its lifetime and it struggles to meet stakeholders' needs. This is observed in the increased amount of communication and time it takes for completion of a task. Stakeholders have different understandings of the process workflow that they adapt to meet their needs. Information is decentralized and not standardize, which predisposes an environment of additional uncertainties and an increase of ad hoc work. Decision making becomes complex and dependent on increasing amount of variables. Stakeholders sometimes end in a conflicting situation that requires escalations in the hierarchy. Last but not least, small amount of the available data is gathered and analyzed, in order performance to be measured. All this contributes to a steady decrease in the level of efficient utilization, i.e. under- and overtime, of the limited resource.

As mentioned before, it is expected in future the amount of configurations and demand to continue to increase, exceeding the limits of available time and physical space. This will force even more the usage of multiple configurations on single systems and a high level of organization. In its current state, the reservation system would not be able to handle all new requirements, which will have a negative impact on the effective use of the resources as well.

1.3 Research goal & objectives

The aim of this research is to find a practical solution to the given problems, therefore, the main goal is to improve and optimize the DTE reservation process and procedures, and the supporting tools and technology, in order to satisfy stakeholders' needs and requirements. Three key objectives were given in the beginning of the project. First, the new process has to maintain the current effectiveness level and to increase the efficient utilization of resources, a goal of 70% of TB utilization was set. Second, the process has to be learning, meaning to gather all relevant information for past events and decision, and based on them to indicate future improvements. Third and last key objective is the new process to provide a certain level of flexibility required to handle dynamic R&D environment. Based on these objective was formulated the main research goal as follows:

"Design a lean and flexible learning scheduling process for MRI development test environment that effectively and efficiently utilizes the limited resources and facilitates decision making."

In addition to the main objectives, three more sub-objectives were set. The first sub-objective is the necessary information for the decision making steps to be standardized. Furthermore, communication waste in the process has to be reduced, and finally, the amount of ad hoc decisions due to junctures has to be minimized.

1.4 Research questions and scope

The focus of this master thesis will lay down on existing scheduling concepts and their application in the new environment of the given case. The development of a scheduling algorithm is left outside the research scope at this moment of time. Therefore, two main research questions were identified, in order to achieve the main goal. The first one will cover the theoretical background from scheduling literature, while the second question will deal with the practical application of the findings. The research questions are defined as follows:

RQ1: What scheduling concepts could be identified in the literature and what are their advantages and disadvantages?

We review the scheduling literature, in order to find the main scheduling concept, on which we can base the design of an improved scheduling process. To achieve this, we first answer the following two sub-questions:

SQ1-1: What are the fundamental elements and basic principles of scheduling defined in the literature?

First, we get familiar with the building blocks of scheduling and what a scheduling process is.

SQ1-2: What similar cases could be identified in the literature?

Then, we review available case studies in the literature that have similar settings and problems, as the ones described earlier.

RQ2: How to improve the current scheduling procedure by using scheduling concepts with regards to stakeholders' complaints and desires?

After the literature review for possible solutions of the current problems, we design a scheduling process for DTE resources that also satisfies involved stakeholders' needs. In order to propose a new process design, we first analyse the current situation and then, we evaluate the process design by answering the following sub-questions:

SQ2-1: How the scheduling of DTE resources is currently done?

We collect information and analyse the current way of working with DTE resources.

SQ2-2: How stakeholders perceive the current DTE reservation process?

We investigate what stakeholders think and what possible improvements they see in the process.

SQ2-3: What are the perspectives for the new scheduling process to improve the way of working?

Finally, we evaluate the designed process and we compare it to the current situation, in order to identify the benefits of implementing it.

1.5 Research model and outline of the report

The research model (see Figure 1-2. Research model) is derived from the research questions. The necessary steps are identified and spread in four stages and five chapters (from 2 to 6). In the first stage we provide the required theoretical background, then we investigate and analyze the current situation in stage 2. In stage 3 we design and evaluate a scheduling process and in the last stage we propose the final scheduling process.

In chapter 2 we perform a literature review, where we answer SQ1-1 in section 2.1 *Fundamental elements of scheduling* and SQ1-2 in section 2.2 *Similar cases from literature.* Based on this information in section 2.3 *Scheduling concepts and trade-offs* we provide an answer to RQ1.

In chapter 3 we empirically analyze of the current situation. In section 3.1 and 3.2 we investigate the *Current scheduling process at DTE* and answer SQ2-1. Next we answer SQ2-2 in section 3.3 stakeholders' *Complaints and desires about current process.*

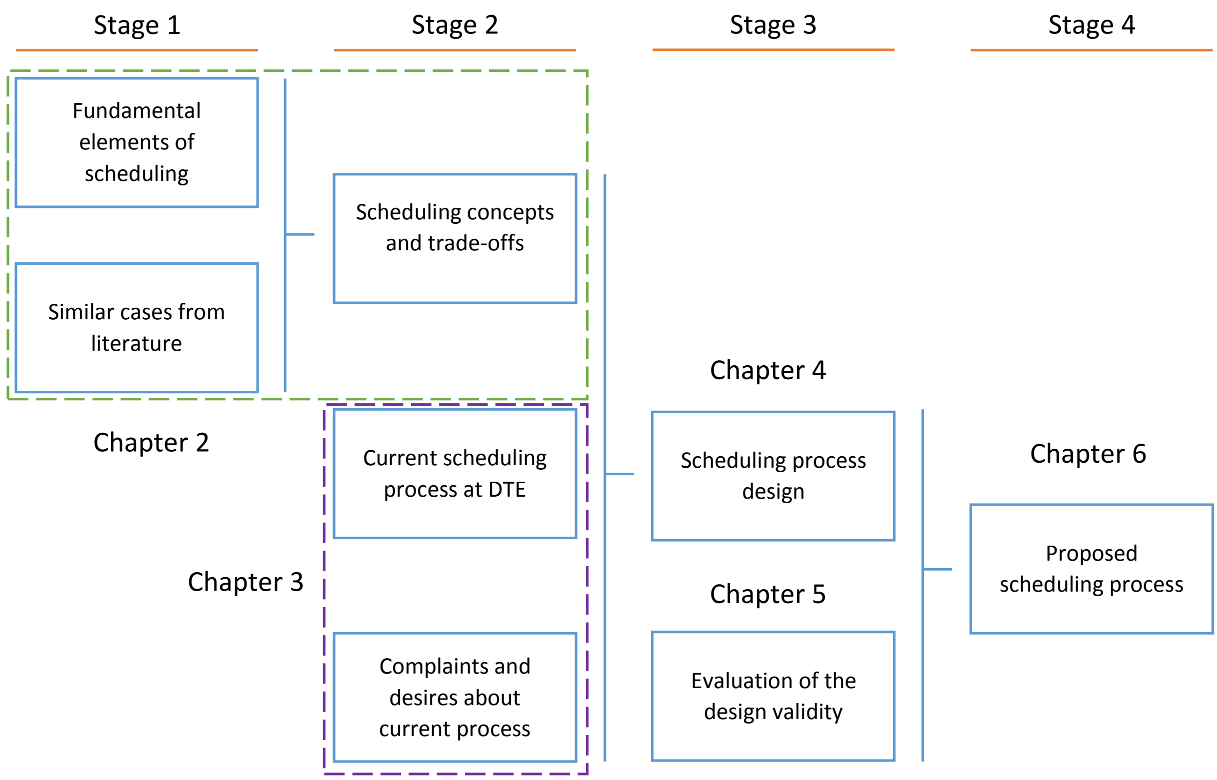


Figure 1-2. Research model

In chapter 4 we provide *Scheduling process design* in order to answer RQ2. Next, in chapter 5 *Evaluation of the design validity* we satisfy SQ2-3. Based on the process design and the evaluation are presented recommendations and final adjustments to the *Proposed scheduling process* in chapter 6.

1.6 Research methods

The research methods used to collect the relevant information for each step in the research model are shown in Table 1-1. Research methods

Table 1-1. Research methods

	Fundamental elements of scheduling	Similar cases from literature	Scheduling concepts and trade-offs	Current scheduling process at DTE	Complaints and desires about current process	Scheduling process design	Evaluation of the design validity
Literature review	○	○	○			○	
Interviews				○	○		○
Documentation				○		○	○
Observations				○	○	○	

2. Scheduling literature

In this chapter we perform a review on the academic literature in order to answer the first research question: *What scheduling concepts could be identified in the literature and what are their advantages and disadvantages?*

2.1 Fundamental elements of scheduling

2.1.1 Scheduling process

Scheduling is defined as "a decision making process that deals with the allocation of resources to tasks over given time periods and its goal is to optimize one or more objectives"[1] (Pinedo, 2008) or as "a mechanism or policy used to efficiently and effectively manage the access to and use of a resource by its various consumers" (Casavant & Kuhl, 1988). The difference between both definitions is the point of view and the scope. The first definition defines scheduling through allocation, while in most cases both could be synonyms, it is important to distinguish scheduling from allocation. They are alternative formulations of the same problem, but while allocation refers to resource allocation (from resources' point of view), scheduling applies to task scheduling (from consumers' point of view). In both definitions could be identify that two of the main components of a schedule are the resource and policy, but the latter definition has a broader view and it also considers the consumer.

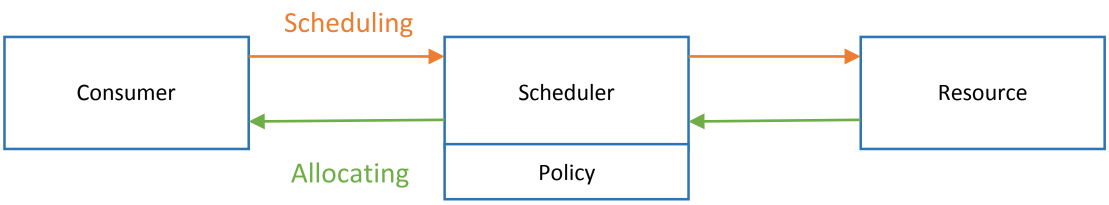


Figure 2-1. Scheduling system (Casavant & Kuhl, 1988)

In order to understand the role of a scheduler, it is important to understand how it affects the surrounding environment (see Figure 2-1.). A scheduler makes decisions based on a policy, a set of principles, objectives, and constrains, which may have impact on either or both resources and consumers. All three - consumer, scheduler and resource perspective are explained next.

A consumer evaluates the scheduling system by his/her satisfaction of the process and outcome. Casavant and Kuhl (1988) state that the goal of a consumer is to quickly and efficiently access the resource, but not to be disturbed with additional work or problems associated with the scheduler. Two properties of the scheduling system are recognized by them: performance – how well the scheduler manages the resource; and efficiency – how difficult or costly it is to access the management resource.

On the opposite, the scheduler is interested in the performance of the scheduling algorithm, which could be defined with two essential criteria (MacCarthy & Liu, 1993): effectiveness or optimality – is a relative difference between desired optimization criterion and actual performance; efficiency – is the computational resources necessary to obtain a solution. Last, the resource is interested only in its efficient utilization – minimization of resource idle time.

[1] Original definition by Baker (1974): "the allocation of resource over time to perform a collection of tasks"

2.1.2 Scheduling environments and models

Offline scheduling

Offline scheduling also called cyclic, static or time triggered scheduling is based on the fact that at a certain moment of time is gathered a finite set of tasks that have to be scheduled. When they are completed a new set of tasks is gathered and a new cycle starts. A requirement for offline scheduling is a thorough understanding of the scheduling system and the environment it will operate in (Fohler, 2011). If these requirements are met, very complex task and environment relations could be described. Moreover, since scheduling is done upfront multiple attempts are allowed to reach the most optimal solution. It is also static, because all necessary decisions are made upfront and they are not allowed to be changed in run time, i.e. rescheduling. The end result of static scheduling is the generation of so called baseline schedule. There are two possible environments that identify the set of jobs considered by offline scheduling – deterministic and stochastic environments.

Deterministic environment

In deterministic environment it is assumed that all information is given and it does not change in time. The output of the model is fully determined by the scheduling algorithm, which makes it highly reproducible and repeatable. Deterministic models are hard to be applied to natural world problems, therefore, they focus on solving theoretical problems. For a comprehensive review of deterministic scheduling models, see Chen, Potts, & Woeginger (1999).

Stochastic environment

Stochastic environments also include natural world's randomness and uncertainty. As in a deterministic environment, the set of tasks is finite, however some variables are uncertain. Uncertainty could be qualified as incomplete or imprecise data (Chaari, Chaabane, Aissani, & Trentesaux, 2014). The most common example for such a variable is the task processing time, however there could be other variables, such as machine breakdowns, new task arrivals, delays and cancellations. The main aim is uncertainty to be modelled as probability distribution, in cases where this is not possible, the key objective is the estimation of worst-case performance ,e.g. see Daniels & Kouvelis (1995).

Online scheduling

Online, dynamic, reactive/adaptive or event-triggered systems do not require an initial set of tasks to generate a schedule, but it schedules tasks at the moment of their arrival. The scheduling decisions are based on predefined rules and the current state of the system. This means that task priority is determined in real time based on the current and not initial conditions (Casavant & Kuhl, 1988). Thus online scheduling cannot handle complex task relations and environments. Duo to the dynamic changes online scheduling could be very flexible, but highly unpredictable.

Hybrid scheduling

Hybrid scheduling is a combination between online and offline scheduling. It is used in environments where aperiodic tasks and events are common and the complexity of complete offline scheduling and unpredictability of complete online scheduling solutions are not suitable solutions. The offline part is the generation of a (baseline) schedule, which may consider stochastic variables. The "online" part are the schedule repairs required based on the occurrences of unexpected events.

2.1.3 Scheduling policies

In any scheduling model, priority has to be indicated in some way or another. There are different approaches to show priority, whether it previously existed or not. Here are listed the main priority rules or also known as scheduling policies, but many more variations exist.

First-come, first-served

First-come, first-served is one of the most applied scheduling strategies, when all tasks have the same properties, such us weight and due dates. It is used in every area where scheduling is required, due to its simplicity. In essence, the only rule is that every task is scheduled to a resource in the same order they came to the scheduler. The advantage of this approach is the minimization of overhead, since context switching could occur only after a task is completed and there is no reorganization of the queue. However, when tasks have different weights, it is often associated with frictions between different tasks. It could be said it is the easiest approach, but neither efficient, nor effective in more complicated conditions.

Round-Robin scheduling

Mainly in computer science and other areas, where preemption is allowed and there is no task priority, a variation of first-come, first-served with better balanced tasks to resources and output is the Round-Robin scheduling. In round-robin approach longer tasks are broken on the granularity of shorter tasks and then executed in circular order. A disadvantages are the possibly large overhead and that it is much fairer to shorter tasks then longer tasks. In addition, if all tasks have same duration and equal cycle time, it is the same as first-come, first-served. If the cycle time is shorter that the task duration, it has potentially lower throughput compared to first-come, first-served, since all tasks are completed at the end.

Shortest/Longest time first

In many cases the duration of a task is considered as directly proportional to the amount of uncertainty and variability. Depending on the desired objective tasks could be ordered in increasing or decreasing rate of their duration. When the longest tasks are scheduled in the beginning it gives flexibility in ordering the shorter tasks at the end, in order to fulfil the whole work load. A disadvantage of longest time first is that the output (completed tasks) is highly saturated at the end of the cycle. On the other hand, shortest time first levels the output and maximizes task throughput, but has poor flexibility.

Highest success probability task first

The highest success probability task is a more general variation of shortest/longest time first, when it is possible to calculate the task variability independently from its duration. The benefits of this approach is that the impact of unpredictable tasks to stable tasks is minimized and throughput is increased.

Highest priority first

All mentioned strategies above ignore that a task may have initially set priority, however, in real world scenarios usually tasks do have different priorities. In scheduling priority is considered as a function of two variables: importance (weight) and urgency (due date). Ordering tasks using highest priority first strategy maximizes effectiveness (the reward), but neglects the efficiency (the cost).

Block scheduling

Block scheduling eliminates the issue with friction between different classes of tasks by grouping them in sequential blocks. The block size could be fixed or not. The benefit is lower overhead and clear indication of ownership, while the drawbacks are poor flexibility and often occurrence of resource idle time between tasks in a block. This decreases both schedule efficiency as well as resource efficient utilization. In addition, block scheduling has poor flexibility.

Modified block scheduling

There are different concepts that describe modified block scheduling, but all of them try to optimize the block scheduling and reduce the resource idle time. In principle it is modified block scheduling, because block scheduling is combined with one or more of the already mentioned or other scheduling strategies. For example, Breslawski & Hamilton (1991) describe it as grouping the longer tasks in a block, followed by shorter tasks in a second block. This way if a gap occurs in the former block a task from the latter could be moved forward. Another variation is when there is idle time in a block, it is either left unreserved or it is released at some known moment of time (Fei, Meskens, & Chu, 2010).

2.2 Similar cases in literature

In the literature review four scheduling problems are considered for potential similarities: stochastic resource-constrained project scheduling, operating room scheduling, computing systems scheduling, and manufacturing systems scheduling. The focus is put on the former couple, since they involve human interactions, which is an important condition.

2.2.1 Stochastic resource-constrained project scheduling problem

A project is defined as "a unique process, consisting of a set of coordinated and controlled activities with start and finish dates, undertaken to achieve an objective conforming to specific requirements, including the constraints of time, cost and resources“ (ISO 9000, 2005). Therefore, three of the most important aspects of project management are planning, scheduling and controlling. From these, scheduling and controlling are identified as the most common causes for project failure (Demeulemeester & Herroelen, 2002).

The resource-constrained project scheduling problem (RCPSP) is defined as a deterministic combinatorial optimization problem and it has many variants. In the basic variant of RCPSP there are given a fixed set of activities and resources. The activities have known durations and some constrains between them, e.g. sequence. In order to be performed, each activity requires one or more resources. The objective functions is to produce an optimal or sub-optimal schedule that minimizes the make span.

However, in real world projects the parameters are prone to errors in estimation and external unexpected influence. The stochastic resource-constrained project scheduling problem (SRCPSP) is a variant of RCPSP that copes with the unexpected events. It adds to the problem different kinds of uncertainty such as task durations, stochastic task insertion, resource availability, resource consumption, breakdowns etc. Therefore, SRCPSP best represents the settings of R&D pipeline management problem faced in this thesis.

2.2.2 Operating room scheduling problem

Operating room scheduling problem is the second similar case reviewed in the literature. The problems faced in development test environment of MRI systems represents the problems that are faced while scheduling patients for surgeries. There are multiple unexpected events that may cause rescheduling, e.g. new urgent patient, similar to machine breakdowns in DTE. Nevertheless, in both cases the environment is stochastic and resources are limited and very expensive.

In their paper Hans et al. (2008) consider the operating room scheduling problem as offline scheduling with stochastic events. They prove that by grouping surgeries with same level of duration variety could maximize capacity utilization and minimize the risk of overtime. This approach could be classified as modified block scheduling using highest success probability task first.

Hybrid models are also recognized in solving the operating room scheduling problem by Fei et al. (2010). They assign blocks to surgeons or specialties on high level and let the surgeons to assign surgeries in their time blocks. However, each week a committee makes a revision of the schedules by using open scheduling strategy and taking in account necessary constraints. The authors conclude that on theory the hybrid model could improve the efficient usage of operating rooms, if it is accepted by the staff, who has to collaborate and follow the process.

2.3 Scheduling concepts and trade-offs

Although some may argue that in the case of project scheduling under uncertainty there are two general approaches – pure reactive scheduling and proactive-reactive scheduling (Vonder, Demeulemeester, Leus, & Herroelen, 2006), other suggest that they are five – reactive scheduling, stochastic scheduling, scheduling under fuzziness, proactive (robust) scheduling, and sensitivity analysis (Herroelen & Leus, 2005). It is obvious that there is no clear consensus in the academic world about scheduling under uncertainty, there are also researchers who classify scheduling approaches as predictive, proactive, reactive methods (Brčić, Kalpić, & Fertalj, 2012) or as simple as reactive and stochastic approaches (Floudas & Lin, 2004).

Table 2-1. Different methods for schedule generation under uncertainty (Herroelen & Leus, 2005)

Prior project execution	During project execution
No baseline schedule	Dynamic scheduling (scheduling policies)
Baseline scheduling with no anticipation of variability (Predictive scheduling)	Reactive scheduling
Proactive (robust) scheduling	Management decisions
Quality robustness	Sensitivity analysis
Solution robustness	
Flexibility	

Regardless of this dispute, in the case of stochastic resource-constrained project scheduling the focus is put on two main concepts – stochastic (proactive) scheduling for schedule generation and predictive-reactive scheduling for schedule repair during execution. In real-world problems on seldom occasions pure stochastic (offline) or dynamic (online) methods could be used as a solution, furthermore, pure deterministic approach is completely excluded as an option. “A proactive or predictive technique will always require a reactive component to deal with schedule disruptions that cannot be absorbed by the baseline schedule” (Van De Vonder, Demeulemeester, & Herroelen, 2007). Therefore, most applied concepts in real-world situations are hybrid proactive-reactive or predictive-reactive techniques, where one or more offline methods, see left column of Table 2-1, are combined with one or more online methods, right column.

2.3.1 Stochastic scheduling

In stochastic scheduling the original deterministic model is transformed into stochastic model, which threats uncertainties as stochastic variables. The objective is to create optimal and reliable (robust) schedules of finite set of tasks in the presence of these uncertainties. While in deterministic models could be applied standard methods of mathematical programming, in stochastic models are required special techniques (Floudas & Lin, 2004). It is the most commonly used approach in the literature for preventive (proactive) scheduling, since stochastic scheduling forecasts and accounts for all possible future outcomes by using functions for either discrete probability distributions or the discretization of continuous probability distributions. In addition, robust scheduling focuses on creating preventive schedules that minimize the effects of disruptions on the performance measure and try to ensure that the predicted and realized schedules do not differ drastically, while maintaining a high level of scheduling performance (Li & Ierapetritou, 2008). For summary on stochastic programming and optimization algorithms, see Table 2-2.

Table 2-2. Summary of stochastic programming and optimization algorithms

Stochastic programming (Sahinidis, 2004)		Stochastic optimization algorithms (Collet & Rennard, 2008)
Programming with recourse		Random search
	Stochastic linear programming	Iterated local search
	Stochastic integer programming	Computational effort
	Stochastic non-linear programing	No free lunch theorem
	Robust stochastic programming	Hill-climbing
Probabilistic programming		Simulated annealing
		Tabu search
		Neural networks
		Genetic algorithms
		Data-level parallelism
		Particle swarm optimization
		Ant colony optimization

Stochastic methods implicitly incorporate uncertainties, however, an increase in the number of uncertain variables causes exponential growth to number of generated possible scenarios. The required computational power and historical data is considered as the main drawback for considering stochastic algorithms for a solution of complex problems with large number of uncertainty parameters (Floudas & Lin, 2004). To ease this computation complexity, for example, Wu, Byeon & Storer (1999) construct a solution that partially specifies the schedule, the unspecified details are left to be clarify in later moment of time.

Proactive methods

Proactive (robust) methods, part of stochastic scheduling approaches, handle uncertainty by creating schedule robustness to unexpected events, in order the generated schedule to remain feasible under various conditions and functional in stochastic environment (Brčić et al., 2012). Moreover, stochastic scheduling does not construct a baseline schedule, while proactive methods do, for baseline schedules see section 2.3.2. Herroelen & Leus (2004a) suggest three possible proactive approaches – redundancy based methods, robust scheduling methods, and contingent scheduling. In addition, any of the solutions in Table 2-2 are also feasible, such as probabilistic methods or optimization algorithms (Chaari et al., 2014). For a review on proactive strategies and algorithms we will refer to Deblaere, Demeulemeester & Herroelen (2011) and Lambrects, Demeulemeester & Herroelen (2008).

Redundancy based methods

Redundancy based methods generate robustness by perturbations of resource and time redundancy. It is common the focus to be on time redundancy, due the higher cost of resource redundancy. These methods provide fault tolerance or temporal protection by extending tasks processing times or by inserting time buffers based on the statistics of used resources, e.g. slack time used by Hans, Wullink, & Houdenhoven (2008), or critical chain project management (Goldratt, 1997). While these methods mainly focus on feasibility, a drawback could be the neglected optimality.

Robust scheduling methods

Robust scheduling methods are the mostly researched proactive methods. The main goal is to generate a robust loading of tasks that minimizes the consequences of the worst case scenario. Such a method is minimax regret, where robustness is seen as best worst case regret performance over all potential realizations. This technique compares cost of different scenarios with the cost of same scenarios but with perfect information. Furthermore, Herroelen and Leus suggest abstraction of resource usage with pair-wise float concept in (2004b), and restricted resources and robust resource allocation with resource flow network in (Leus & Herroelen, 2004). While robust scheduling achieves high level of effectiveness and low cost (compared to worst case scenario), a drawback could be inefficient resource utilization due conservative schedules.

Contingent scheduling

Contingent scheduling generates multiple schedules to handle different scenarios based on prior predicted disruptions. It could be seen as reactive strategy, since schedule is change during an execution, but it is a proactive strategy due the fact that schedules are generated upfront. It is clear that the focus is not on schedule robustness, but on schedule flexibility (Herroelen & Leus, 2005).

2.3.2 Hybrid scheduling

Predictive-reactive is a hybrid solution of offline and online methods. Some academics do not distinguish proactive from predictive (Van De Vonder et al., 2007), since the goal of both methods is to generate a baseline schedule. However, the difference is that proactive approaches consider variability, while predictive approaches do not, see Table 2-1.

Predictive scheduling

The term predictive scheduling emerged relatively soon in project scheduling literature as a part of the concept of reactive scheduling (Herroelen & Leus, 2005). The authors define predictive-reactive scheduling as “repairing the baseline schedule to take into account the unexpected events that have come up”. However, this repairing or revision activities take place in the reactive part, during project execution. The predictive part is responsible only about the generation of a baseline schedule with deterministic approach. With other words predictive methods ignore the uncertainty and rely on the information that is known at this moment of time. This ease the upfront decision making compared to proactive approaches, but it could result in projects being late, over the budget or even become infeasible. Therefore, proactive schedules serve as better approach for the generation of baseline schedule and respectively better communication basis between project entities (Brčić et al., 2012).

Baseline schedule

The baseline schedule, also called initial/original schedule, predictive schedule or preschedule, plays a vital role in project scheduling (Mehta & Uzsoy, 1999). It has a twofold function, the first is to allocate resources to the different activities, in order to optimize one or more objective functions. The second and very important function is to serve as a basis for communication and coordination of external or internal customers. “Based on the baseline schedule commitments are made to subcontractors to deliver materials, support activities are planned (setups, supporting personnel), and due dates are set for the delivery of project results” (Herroelen & Leus, 2005). The baseline schedule is considered as the best possible scenario at the moment of its creation.

Reactive scheduling

The main purpose of reactive scheduling part is to update the schedule in a response to a disruption or other event to minimize its impact (Vieira, Herrmann, & Lin, 2003). Wu & Li (1995) defined rescheduling as iterative process with three steps – evaluation, solution, revision. The first step evaluates the impact, in case the impact is not serious next step comes in, otherwise, no actions are required. The next step is to find a solution that enhances the performance of the current schedule by using a rescheduling technique. Third step is the existing schedule to be updated or replaced by a new one. It is clear that choosing a solution is the most difficult part and there is no best option (Vieira et al., 2003).

Rescheduling

Rescheduling is the main activity in the reactive process. First, it is worthy to know when a rescheduling is justified. There are four main reasons to cause a reschedule of an existing project schedule shown on Table 2-3.

Table 2-3. Reasons for rescheduling in project environment (Chaari et al., 2014)

Time-driven (Periodic)	Event-driven
Regular time intervals	Unexpected event appearance
	New task arrival
	A given threshold of number of tasks

Vieira, Herrmann & Lin (2003) present an a comprehensive list of unexpected events, also called rescheduling factors, in machine environment (see Table 2-4). In addition, the authors point out that the occurrence of a certain event could trigger another event. The moment of time when a schedule is created or revised is called a scheduling point, while the time between two scheduling points is called rescheduling period.

Once a schedule is no longer feasible and a rescheduling is required, there are two possible solutions – schedule repairs or global reschedules. Since it is assumed that the baseline schedule is a good starting point, schedule repairs are the preferred approach for minimum deviations from the original schedule. However, schedule repairs could be very limited option, therefore, most researchers focus on global reschedules.

The most elementary repair action is the right shift rule, which postpones each remaining task. It is called right shift, because time is always positive and represented as the abscissa. When a task is postponed it moves to the right. Although it is a very simple heuristic algorithm, it tends to have bad performance (Brčić et al., 2012).

Table 2-4. Rescheduling factors in machine environment (Vieira et al., 2003)

Unexpected events	Triggered (follow-up) events
Machine failure	Overtime
Urgent job arrival	In-process subcontracting
Job cancellation	Process change or re-routing
Due date change (earliness/tardiness)	Machine substitution
Delay or shortage of materials	Limited manpower
Job priority change	Setup times
Rework or quality problems	Equipment release
Over- or underestimation of processing time	
Operator absenteeism	

Partial or local scheduling repairs reschedule only the directly or indirectly affected tasks, therefore, it is also called affected operations rescheduling (Abumaizar & Svestka, 1997). The ultimate goal of this method is to preserve the baseline schedule as much as possible. Early start policy in a resource flow (Van De Vonder et al., 2007) is a partial repair, where tasks' could flow in the timeline of a single resource. Early start is a special case of right shift rule, when there is a delay. However, the difference is that in the former case, activities are affected only on the resource, where the delay occurred, and not to all resources. Respectively, when there is an early task, following activities are moved earlier in time.

Activity lists or queues is an ordering of all tasks that can be transformed into a schedule at any time. At a schedule disruption, activity list are scanned for activities that have not started yet and fit the best the possible gaps in the schedule (Chen et al., 1999).

Another method for partial repair is the well-known activity crashing. The goal is to accelerate activities, in order the schedule to go back to its initial state. Similar approach is the match-up rescheduling, where the goal is again to return to the baseline schedule as soon as possible. However, tasks could be rescheduled only in certain period of time after the breakage, which is as small as possible. For more on match-up scheduling, see (Akturk & Gorgulu, 1999; Moratori, Petrovic, & Vázquez-Rodríguez, 2012).

The final reactive method mentioned in the literature is global, total, or complete rescheduling. Essentially, every task that is not processed before the next rescheduling point is rescheduled in a completely new schedule by applying the same scheduling algorithm used for the creation of the baseline schedule but with the remaining set of tasks (Van De Vonder et al., 2007). It is a reset point for the scheduling process. However, in case of contingent scheduling or sensitivity analysis, alternative schedules, which are already generated, replace the baseline schedule.

2.3.3 Trade-offs

Two main scheduling concepts for stochastic resource-constrained project scheduling were identified in this chapter – proactive-reactive scheduling and predictive-reactive scheduling. Both strategies have their strong and weak parts towards different environments and respectively, towards different objective functions. The literature is mainly focused on minimizing two key objective functions – project makespan and project cost. A different perspective for performance measures are – scheduling efficiency, schedule stability, and cost (Vieira et al., 2003).

Proactive-reactive scheduling

Proactive-reactive scheduling by far has the best performance regarding baseline schedule robustness and stability (Van De Vonder et al., 2007). These methods examine possible outcomes and develops schedules to handle uncertainty before even appear. The main goal of proactive approaches is to create a feasible schedule that prevents the worst case scenario.

However, proactive scheduling also have many drawbacks. The first and most important is that it relies on large set of historical data to be accurate, although with time, accuracy continues to improve. Furthermore, most methods focus on robustness or with other words, the successful execution of the scheduled activities. In order to achieve high level of effectiveness, time and resources are sacrificed in redundancy. Although it is done to prevent even higher costs or longer makespan of the worst case scenario, in some cases it may be unjustified solution.

The majority of proactive solution focus on sub optimal solution that handles a single uncertainty event due the exponentially increasing complexity of incorporating more. Choi, Realff & Lee (2007) calculated more than half of billion possible outcomes for the case of a new project arrival in multi-project environment. Their example consists of three running projects and two project candidates, each with three to four tasks. This leads to the conclusion of the enormous computational power required for solving a more complex case.

Predictive-reactive scheduling

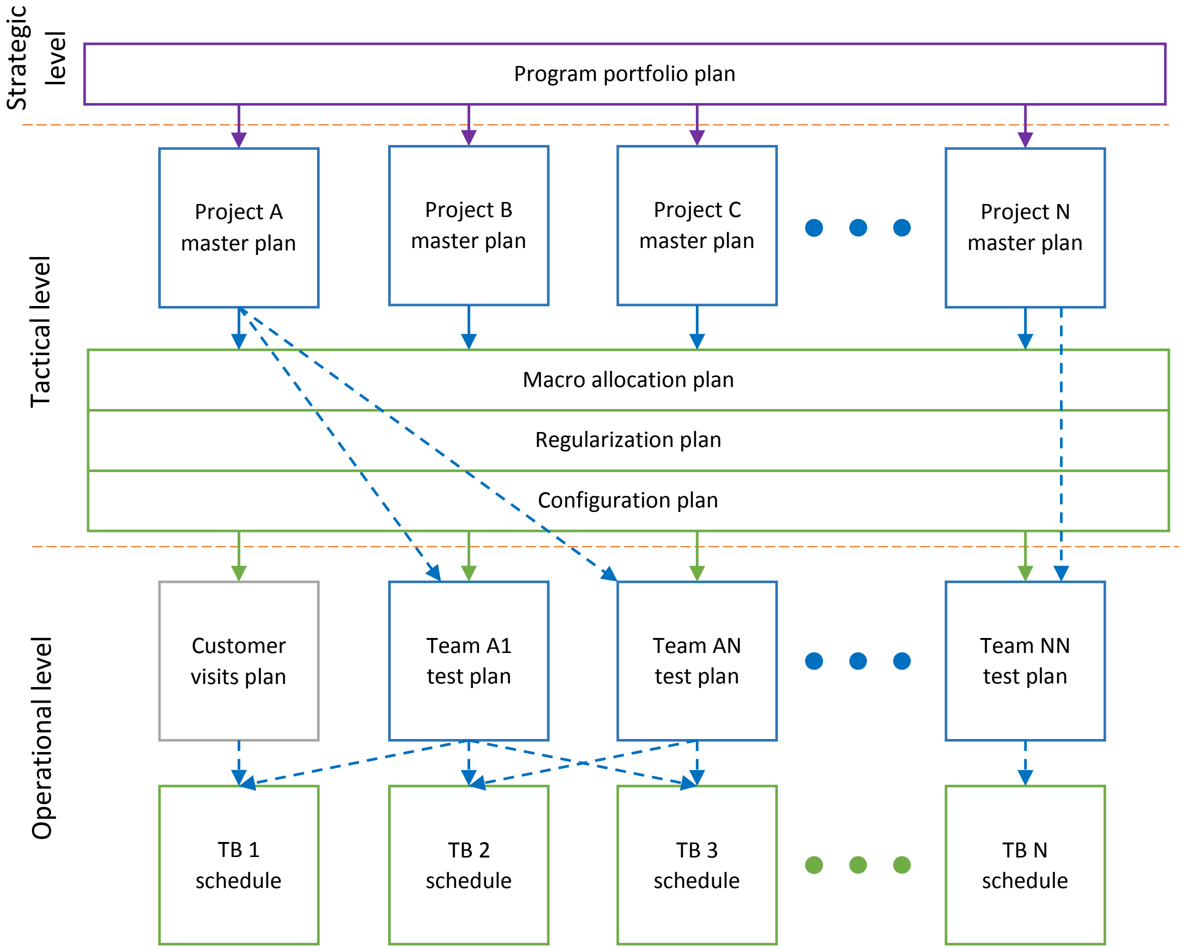
Predictive-reactive scheduling does not consider variability but makes decisions based on the available information at the moment. Thus, it is more relaxed solution than proactive methods. The main goal of these techniques is to support risk (Chaari et al., 2014). Therefore, predictive-reactive scheduling is often used in highly perturbed and/or complex environments, where uncertainty is too great. Predictive baseline schedules could be infeasible, which will have negative impact on project makespan and project cost (Brčić et al., 2012). Therefore, fast and easy for consumers to understand decisions are essential in the reactive part. For more trade-offs of predictive-reactive scheduling or classical (traditional) project scheduling techniques, see (Demeulemeester & Herroelen, 2002).

3. Current situation

In this chapter we investigate and describe the current situation of the process of scheduling the development test environment at Philips.

3.1 Decision levels

The distribution of resources is done on three decision levels – strategic, tactical and operational level. On strategic level leadership team creates a program portfolio plan, where the content is decided, capacity and priorities among different programs and key milestones for them. The strategic decisions are part of the strategic planning and their aim is to construct an attractive portfolio of R&D programs (Subramanian, Pekny, & Reklaitis, 2001). The focus will be put on the tactical and operational decisions that refer to the temporal assignment of limited resources to tasks and vice versa that are required for the actual execution of a portfolio.



3.1.1 Tactical level

On tactical level is decided the resource allocation among the different programs and respectively the configuration plan to satisfy the demand. However, there are two more plans that are independent from programs plans.

The first is the plan for customer visits, which in most cases has the highest priority in using a TB. There are 5 customer bays out of 15, each one with different configuration. Customer visits could be announced from one to several weeks upfront. These are non-elective cases and all TB schedules have to be aligned to them. They cannot be canceled or rescheduled, except if the decision comes from the customer, or in extreme cases, e.g. machine breakdown. Currently, customer visits plan is visible only after a reservation is made in the system.

The second plan is called “regularization plan”, which is the planned maintenance activities. Each 9 to 12 months an MR system is returned and replaced with a new one from the manufacturing department. Depending on the DTE development support capacity the regularization period for a system is from 3 to 4 weeks. Currently, the plan is visible after a block reservation is made in the reservation system for that period.

The macro allocation meeting is a monthly meeting that aims to align different program requests and build a TB configuration plan for the coming months based on their requirements. A major challenge in building this plan is the setup time required for reconfiguring a system. An MRI scanner is a complex system and even changes only in the software, requires couple of days of adjustment of the system, when a hardware change is required this time could be even higher, depending on the required change. Some of the programs work on a project specific configuration, which means that the configuration is suitable only for their needs. The level of modification depends on the project specification, but in general a TB could be not modified, partly modified, or fully modified.

There annual programs related to quality (reliability), productivity or other performance characteristic that requires continuous improvement. These projects may require multiple configurations in parallel. Another type are the new product introduction (NPI) projects, which follow the V-model (Forsberg & Mooz, 1991) process for software and hardware development. They work on new features that are not yet released in the field. Compared to the rest of the programs, these projects have the highest level of uncertainties, due the nature of their work. There is also a clear separation between the stages, where it is assumed in integration and verification stage the level of uncertainties is much higher compared to validation stage.

So far, planned or elective activities were discussed, however, there are also projects that focus on (problem) reports from the field that could be non-elective, similar to customer visits. These requests investigate issues, which could have different urgency levels. Nevertheless, all of them require a configuration that is the same or similar to the released to the customer, in order to investigate the issues.

To sum up, the output of the macro allocation meeting is a configuration plan of the test bays and a plan for the test bay allocation plan among programs, which indicates directly the task priority and high level sequencing (weeks) on each machine.

3.1.2 Operational level

On operational level all plans come together and the final schedule is created. Elective activities are scheduled by their owners and time when this happens vary from hours to weeks. Friction between different parties occur mostly on this level for different reasons and most of the time conflicts are solved here. Most of the rescheduling decisions are taken on the occasion of different events, e.g. delayed activities due unexpected test results, machine malfunction, or higher priority interference, such as customer visits. Another reason for task overlapping is that employees schedule activities well in advance or schedule an activity on a machine that is not allocated to them, both of which are not aligned with test plans of the owner of the machine.

3.2 Scheduling procedure

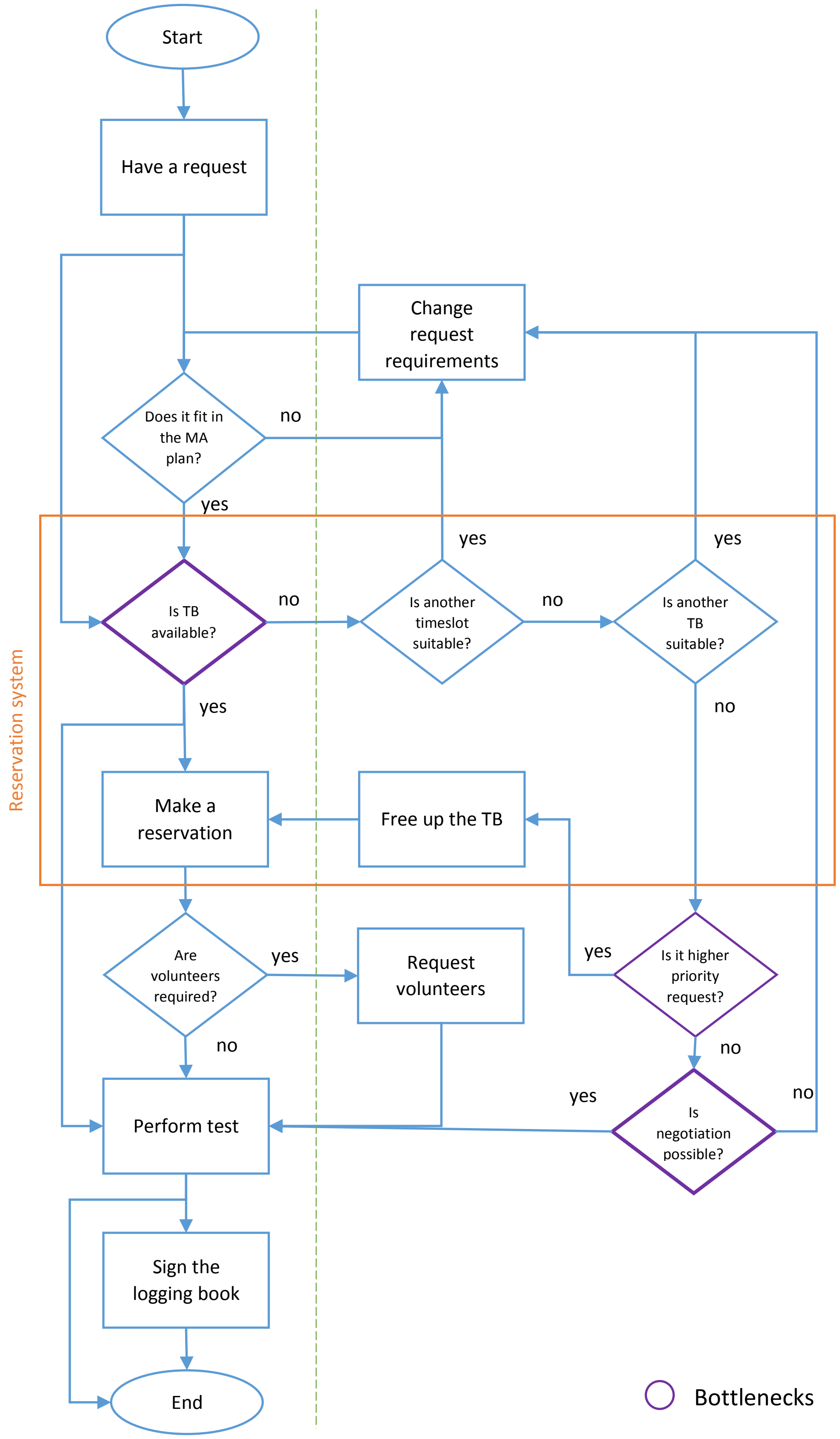


Figure 3-1. TB reservation procedure

On operational level with defined macro allocation plan and configuration plan, the scheduling procedure starts when an employee has the need to use a TB, in the majority of time for testing and in rare cases for something else, such as training. Employees become aware of the macro allocation plan in different ways: they participated the macro allocation meeting, they were informed by their manager or colleague, or they saw the plan located on a shared drive. Based on the macro allocation plan, if the request fits the plan they check the reservation system for available TB, otherwise they have to refine their request to fit the plan. In rare cases, employees are not informed about the macro allocation plan and they directly proceed towards finding out if a TB is available. If it happens on the moment, some employees go directly to the TB hall to check if the TB is available, otherwise, the only way to find future TB occupation is through the reservation system. If the testbay is available, then the employee could reserve the time slot that is required, or in some cases of very short tasks to perform them on the moment without registration. When the reservation is in place, if volunteers are required for the tests, they are ordered about one week upfront. After each activity performed in a TB, employees are required to sign and write a description of the test in a logging book located at the testbay. However, duo different reasons in seldom occasions it may happen that the logging book is not signed.

In the case when a TB is not available, most frequently employees search for different timeslot in their requirements and they start the search again. However, if different time slot is not possible, then employees change their requirements towards the required machine and try to find another suitable option. If this is also not possible, then a conflict between two activities arise. The key factor for solving this problem is estimating the priority level of both activities. In some cases, it is directly inherent from the tactical or in rare cases from strategic level, on the other hand, when this is not possible, it has to be find out on the moment.

An escalation system takes place (see Figure 3-2. Escalation system:Figure 3-2), where if a decision is not achieved on the same level, then it is escalated to one level higher. In case the final decision is that the contender has higher priority, then the former reservation is canceled and replaced by the new one. In the alternative case when the request does not have higher priority, an option is to negotiate with the time slot owners to fit the new activities inside their time slot. If this is also not an option, the requester has to redefine the TB requirements of the request.

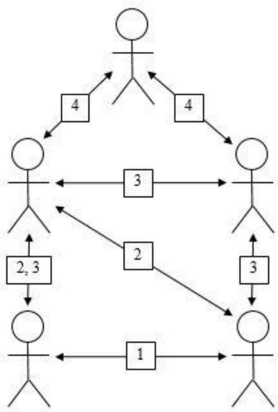


Figure 3-2. Escalation system:
1st case – same level
2nd case – one level higher, same manager
3rd case – one level higher, different managers
4th case – more than one level higher

Since it is an open system, currently the way of working is FCFS with elements of pure block scheduling. The FCFS approach is the easiest and fastest way of working, if there are enough available time slots, however, in this case the resource is limited and frictions start occurring on increasing rate. This means that the non-desirable right part of the procedure (see Figure 3-1) has become more active. Cancelations have huge negative impact on the schedule, causing many rescheduling, and on the employees' satisfaction level. In order the bottleneck to be removed from the decision making step of priority level, a new practice of block scheduling start working. With block scheduling the priority level is clearly indicated on some TB which reduces the number of cancelations, however, it start creating a bottleneck on the next step in negotiations and even earlier on the TB availability. In order to prevent configuration changes, project teams does not release their reserved time when they do not need it, which significantly impacts the resource utilization efficiency and other employees' satisfaction.

3.3 Stakeholder complains and desires

Twelve interviews were performed with a representative out of 13 identified key stakeholder groups (see Appendix C: Stakeholder analysis. The first goal of these interviews was to gain domain knowledge about the workflow/processes and responsibilities/roles in the MR R&D department. Moreover, the main goal was to understand the current situation of using DTE resources. The stakeholders were asked to identify the good and bad parts of their work involvement with DTE. The settings of the interviews could be find in Appendix C: Stakeholder analysis.

Overall, stakeholders did not have serious complains, but everybody had ideas how it could be improved. The majority of stakeholders focused on the tangible part – the reservation system, but some of them addressed also the reservation process. This was expected since their work involves mainly using the tools behind the process. Moreover, almost everybody was seeing the process slightly different than the one before. A reason for this could be the fact that the process is not strictly defined and there is room for free interpretations.

The major elements that stakeholders like in the current situation are:

- The reservation system is an open online tool that could be used by anybody
- The reservation system is stable
- The reservation system is simple and easy to use
- The reservation system contains most of the required information (SW & HW configurations)
- The macro allocation plan as part of the reservation process

There are four major points for improvement that were mentioned by everybody in some way or another:

- Better overview

The key element that stakeholders would like to be improved is the overview on both tactical and operational levels. For example, high level leads would like to see different reports and long term planning, in order to make better plans. Low level leads would like to see overview of their team's activities. Stakeholders outside PRP would like to see the macro allocation and some specific information, such as peripherals location, actual person who is currently in TBs, TB technical availability (regularization plan) and others. Some general elements are also the technical status of test machines in any moment of time, better description of what test were done and others.

- Better process control

Many of the leads inside PRP would like to have better control over the reservations inside the allocated time for their team. They would like to freely allocate their team's activities or let their team's do it for themselves inside of the time allocated for them. In addition, they would like to be notified for any other requests outside of their team that will interfere with their work.

- Better schedule stability

Many of the teams experience cancelations and rescheduling activities. Stakeholders would like to stay on the straight forward process without the complications and uncertainties of rescheduling events.

- Better system functionality

The main functionality improvement that stakeholders would like to see is better integration between different tools and system involved in the reservation process. There are also many other small functional requirements that will make work easier and more pleasant. One of the most mentioned is implementing queues for TBs with notification to the queue when a TB is freed earlier.

4. Scheduling process design

In this chapter we answer the second research question: *How to improve the current scheduling procedure by using scheduling concepts with regards to stakeholders' complaints and desires?*

4.1 Hybrid scheduling strategy

4.1.1 Scheduling strategy

Based on the reviewed literature two main scheduling concepts were distinguished: proactive-reactive scheduling and predictive-reactive scheduling. The former strategy relies on a heavy set of historical data, which is analyzed using various mathematical models and algorithms. The aim is to estimate the probability of different events happening and to prevent the "worst case scenario". On the other hand, predictive-reactive scheduling takes a deterministic approach by creating a baseline schedule on the basis of already present information. When a stochastic event happens, it is reacted to it in real-time and the schedule is adapted to the new situation. The main trade-offs of both concepts are that proactive scheduling offers robust schedules and better learning curve, while predictive scheduling has broader range and can handles very complex environments with high level of uncertainty.

One of the main requirements for the new scheduling process was to be a learning process, which gives weight on choosing stochastic scheduling for a solution. However, as noted few times before, stochastic scheduling requires a significant amount of data to be effective and even more to be efficient. The current gathered data from the reservation system is not sufficient enough in quantity and quality for a stochastic algorithm to take place. In addition, in multi-project R&D environment almost every type of uncertainty exists (see Table 2-4). Therefore, predictive-reactive scheduling is selected as better solution at the current moment of time. However, due the undisputable benefits of proactive strategy, the data has to be gathered in a structure manner with the mindset of a proactive method taking place in future. Attention will be put on new task arrivals, over- and underestimation of processing time and setup times.

Predictive-reactive scheduling is a more appropriate solution for the current situation than stochastic scheduling for several reasons. The first already mentioned reason is the insufficient historical data. However, a significant factor is also that predictive scheduling is closer to the current situation than stochastic scheduling, meaning less effort will be spent in the transformation process. The current way of working was shaped on the basis of cyclic meetings and the construction of initial plans, which later were updated when required. Moreover, the culture at the company and desires of stakeholders are clear that the element of an open system and decentralized decision making are highly valued and appreciated. Hybrid scheduling provides flexibility that is harder to achieve with stochastic scheduling and much required in the dynamic environment of new product development.

The decentralized decision making in the manual construction of the schedule, however, also limits the implementation of a mathematical algorithm to automate the distribution of activities. This means that the output of the process will still be vulnerable to human mistakes. In order to improve and limit as possible this exposure are suggested some generic changes (see section 4.2) that could be adopted on both tactical and operational level.

4.1.2 Scheduling policy

Block scheduling

Block scheduling is selected as representation of priority in the schedule, due the multi-level manual and distributed decision making in the process and the necessity of clear indication of ownership. Although blocks may have different size, they are often connected with inefficient utilization of resources by block owners. For this reason, a block hierarchy is created.

Block Hierarchy

The benefits of having a block hierarchy is two-fold. First, it will increase visibility inside blocks, and respectively improve the overview for other consumers. In the case of inefficient utilization, block owners could experience guilt, learn and better perform next time. Second benefit is the authorization of distributed decision making by the different consumers. However, a drawback could be the unwillingness of some stakeholders to take the responsibility that comes with the block ownership. Therefore, the process has to minimize as possible the administrative work in managing the blocks.

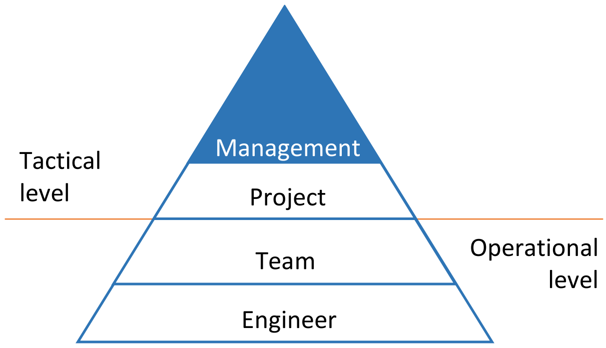


Figure 4-1. Hierarchy in blocks

Blocks are first created on tactical level where resources are allocated to different projects. The authority is passed to the project (program) manager responsible for the project. Further, each project block is further separated between one or more project teams. Finally, team leads or test engineers themselves schedule tasks to be performed on the allocated resource. The information transparency is considered as adequate stimulus for block owners to use as efficient as possible the allocated time.

4.2 Generic improvements

4.2.1 Information standardization

Most important generic improvement regards the information standardization throughout the whole reservation process. Information standardization will improve the information overview and transparency, in addition will help in the decision making steps. As mentioned in the literature the baseline schedule plays a vital role in project scheduling and it serves as a communication and coordination tool for internal and external entities. Therefore, both the baseline schedule and the inputs for its generation must have a standard form.

Tactical level

On tactical level the currently used macro allocation plan could be used as a baseline schedule. It contains the information for testbay regularizations, testbay configurations and the time allocations for different projects and big activities, such as workshops. The request for a macro allocation is done by the project (program) manager or a representative of him. It consists of a project plan with the major activities that are going to be performed on one or more testbays. While it is preferable these plans to have uniform format, they also represent different management styles of different project managers, which could be more important. However, an important factor for adequate decisions is activities to have duration, start and end dates.

Operational level

On operational level the baseline schedule is the final schedule in the reservation system. It must give indication of what, when, why and who is using a resource. Resource properties have to be centralized and standardized. Moreover, a standard request form has to be implemented, which consists of all required information for the schedule generation, as well as the schedule revision. This will drastically improve the information overview and respectively decrease the communication between different consumers in the process. For description of the request form see section 6.3.1.

Testbay properties

The most important element that has to be added to the description of a testbay resource is the active technical status at any moment of time. In general, a TB could be off-field, when magnet field is off, and three states of on-field – not operational (serious system defect), partly operational (partial system defect), and fully operational (no system defects). In addition, allocation status has to be introduced, where possible options are – open (no allocation), shared (allocated to two or more projects), dedicated (allocated to a single project), and regularization (planned maintenance).

The second set of properties are related towards the system configuration description. There are three general parameters that could be associated with each configuration – production equivalent materials (yes/no), volunteer release (yes/no), and remote access (yes/no). Production equivalent materials stands that a testbays is build complete with at least pre-production materials or post materials. A system is released for volunteer scanning, only if a set of safety regulation tests is passed. If a system is production equivalent, then it is automatically also volunteer release, however, the other way around is not true. Remote access indicates, where it is possible to use a system from distances or not.

A system configuration consists of two parts – hardware and software configuration. In many cases both parts are interconnected and could be used as analogues. Although a certain hardware configuration could support a certain software release or higher, there are software packages that support older hardware configurations. A hardware configuration could be described with main configuration fields and detailed configuration fields. The main configuration parameters are system type, magnet strength, and acquisition. Whereas some parameters could change and become irrelevant in time, such as type of acquisition. The detailed configuration consists of full description of all installed hardware components on the system.

The software configurations are usually described with software releases or software streams that are installed on computers, called software hosts. A testbay could have multiple hosts and respectively, to support multiple software streams. In addition, testbay adjustments could be required for some software installments or patches. Therefore, testbay description should also include the available software hosts, installed software packages on each of them, and the currently running software release.

4.2.2 Time representation

Choosing time domain representation plays a vital role in the coordination of activities and in the efficient use of resources (Jain & Grossmann, 1999). There are two main approaches of time domain representation: discrete time representation and continuous time representation. Under discrete time representation is understood time slots that are equally sized time intervals, while in continuous time representation there are no boundaries on the interval size. The benefits of using discrete time representation is the easier time management, however, a drawback is the inaccuracy and respectively inefficiency, due to the fixed interval sizes. On the contrary, continuous time representation offers accuracy, but on the cost of more time management. Although discrete time representation inevitably includes time losses, a continuous time representation's accuracy is not required in the given case. For a comprehensive review on continuous-time versus discrete-time approaches, see (Floudas & Lin, 2004).

The current system (see section 3.2) offers the opportunity of reserving time slots with granularity of one hour. Although it is structured and easier to operate with, many stakeholders recommended using smaller size time slots duo to the fact that some activities are shorter or not multiple of an hour. Ultimately, the current time slot size gives opportunity for time waste, which results in underutilization of the resource. In order to prevent underutilization duo to process/time restriction, such as one-hour time slots, smaller granularity would improve the process by allowing stakeholders to be as accurate as possible. However, having a structure in the time allocation is also highly preferable and important. Therefore, it is suggested time slot granularity to be one to five minutes, but time slot sizes of half an hour to an hour to be the proposed size to the consumers when they schedule a task.

4.2.3 Time horizons and periods

Another generic improvement associate with time is defining a time horizon. The current horizon is open with no time limit in scheduling an activity. This allows consumers to schedule activities far ahead in time or back in time, without having a necessity other than to insure they will have time in future. In addition, needs and priority change with time and by allowing reservations in the far future, the chance of cancelation and rescheduling is significantly increased. In order to prevent this, two-fold improvement is suggested – the introduction of planning period and commitment period, based on the different cycles in the process. For better illustration and an example of the time horizons, see Figure 4-2. Time periods.

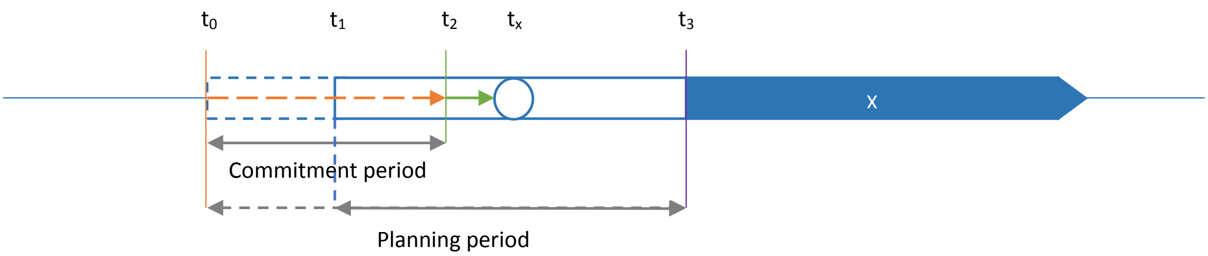


Figure 4-2. Time periods

On this example, a consumer at time t_0 schedules an activity at time t_x. The planning horizon is t_3 and it is the end of the visible timeline. Depending on the type of request, the planning period starts either from t_0 or from t_1 and it ends at t_3. The commitment period starts from t_0 and it ends at the commitment horizon t_2, which is a fixed time before t_x.

Planning horizon

Tactical level

The first and biggest cycle is the regularization activities, which are planned on tactical level and happen every nine months per a testbay. A regularization is the preferred time for the replacement of a main configuration, therefore, requests for new or non-existing main configuration (t_x) have a maximum time horizon in nine months (t_3). The minimum time horizon is dependent on the lead time for the delivery of a new system from the manufacturing department, which is three months (t_1).

The second cycle on tactical level is the macro allocation meeting, which happens once a month. On the macro allocation meeting are reviewed requests mainly for the existing configuration, which gives a minimum of one month planning horizon for a request for existing configuration (t_1). Duo the standardization requirement every request to be supported with existing test planning (see section 4.2.1) it is not visible to assume that manager will have a detailed overview of test activities in more than three months (t_3).

Operational level

There are two requests that are special compared to the normal test requests and they are the customer visit and the annual workshop/training requests. The customer visit has the highest priority in using a test facility, while annual workshops normally last for a week and fully occupy many testbays. However, duo to the introduced planning horizon on tactical level, it is safe to assume that a detailed configuration plan would not be able to fully guarantee what could happen in more than six months. Therefore, it is suggested the planning horizon of these two type of requests to be no more than six month (t_3). Customer visits could be unexpected and could be announce in a month or in even in a week, which makes ineffective to define a minimum barrier for their planning (t_0). On the other hand, workshops are planned well in advanced and should be defined before the distribution of macro allocation, which means they have to be announced at least three months ahead (t_1).

The last, but most frequent type of request, is the general test requests. Since these requests are highly dependent on the macro allocation plan, which is updated each month, it is suggested the maximum planning horizon for a general request to be one month (t_3). In order to allow maximum flexibility, a minimum planning horizon should not exist. This will allow ad hoc reactions to fulfil empty time spaces, if necessary. However, there is one exception of the general test request and it is related to the test done with volunteers. Volunteers have to be requested at least one week before the date they are required. This limits requests for volunteer scan tests to have a minimum of one week planning horizon (t_1). For this reason, it is suggested the scheduling cycle for operational level requests to be once per week.

Commitment horizon

So far in this chapter were discussed only requests instead of reservations. Commitment horizon is suggested to handle and shape the distributed decision making on operational level. While on tactical level it is adopted that on a macro allocation meeting everybody commits in the macro allocation plan for the next month, on operational level such practice does not exists. A known practice is the use as leverage the fact that somebody was first (FCFS), however, this could not be the decision factor in a limited resource environment.

Scheduling or rescheduling points symbolize the start and end of a scheduling cycle, where scheduling decisions are made. The scheduling cycle is called rescheduling period, in this case commitment period. The emphasis is put on commitment, because it is essential to underline the importance of utilizing limited resources. Therefore, based on the scheduling system on fig. Figure 2-1 is distinguished two side commitment, one is the consumer (requester) and the other is the resource commitment (owner).

Consumer commitment

The consumer is the initiator of the process and as such, he or she carries the responsibility to advocate its request for a resource in front of the scheduler. This is done by providing an established plan of one or more activities that require a resource involvement. The consumer automatically commits when a request for a resource is submitted (t_0).

Resource commitment

In order a consumer request to become a reservation, the resource owner has also to commit to it. This could happen immediately after the request submission, e.g. in the case of dedicated project TBs, or until the end of the commitment period, which is the scheduling point before the requested time. It is important to mention that commitment horizons differ from planning horizon, because planning horizons have fixed time period ahead, while commitment horizons depend on the requested date. From the example of Figure 4-2, if t_0, t_1, and t_2 are scheduling points the rescheduling point and respectively the end of the commitment horizon for t_x is the last scheduling point t_2.

4.3 Four step process – 4C

From the scheduling system (see Figure 2-1. Scheduling system (Casavant & Kuhl, 1988) are distinguished three roles – consumer, scheduler and resource. The consumer has all the knowledge about the task that has to be performed on the resource. Therefore, the consumer is the only one who can define the task and all the requirements towards the resource. Moreover, in the case of predictive-reactive scheduling, this has to be done beforehand. The scheduler is the intermediary between the consumer and the resource, and its purpose is to schedule the consumer's tasks to the resource. In the suggested strategy two key elements of scheduling are self-evident– the generation of schedule (predictive part) and the schedule revision (reactive part) (Li & Ierapetritou, 2008). Finally, tasks are performed using the resource.

Based on these four elements was designed a scheduling process (Figure 4-3) to facilitates the decision making. The process consists of four sequential phases: Construct, Check, Commit, and Complete; respectively for task definition, schedule generation, schedule revision, schedule execution.

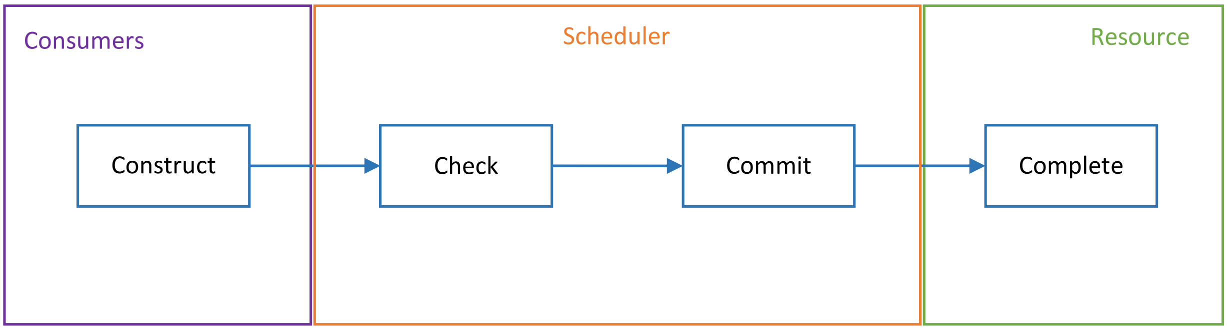


Figure 4-3. 4C process

In the first step all available information is gathered and the consumer *constructs* a request. In the next step resource availability is *checked* and the request is aligned and scheduled in the existing schedule. When all parties agree and *commit* to the new schedule, schedule is executed and activities are *completed*.

4.3.1 4C process activities

The 4C process activities are uniform and their description could be applied on both tactical and operational level. In Figure 4-4 could be seen the different actions per step. In the first phase requests are defined. This information will be later pass on through each step of the process. Information gathering is also extended during the check step, due the distributed gathering of information. Only in the second phase a consumer could see the existing schedule and pending requests of others. The most important action in check is to align different requests and put them in a time frame. While the main activity in check is the generation of the new schedule, some of the decision making is extended through the commit phase, where is done the schedule revision. However, if a schedule requires a repair, it will be push back to check phase. Final step of the process is to complete all activities that it has been agreed on.

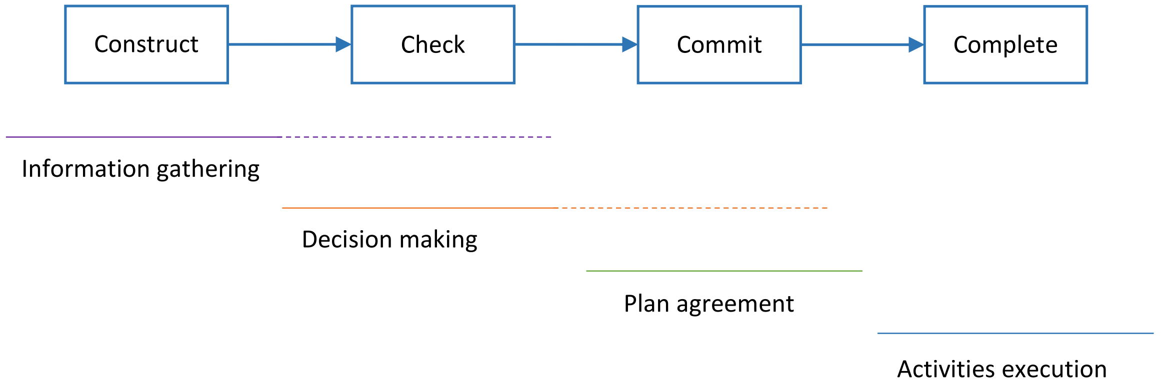


Figure 4-4. 4C process step actions

4.3.2 4C process on tactical level

The process takes place on both tactical and operational level. Whereas in the complete phase on tactical level, the same process starts on operational level. However, although the steps are similar deliverables are different.

Process deliverables

The first deliverable after the construct phase is the submitted project plan by a project manager. In this plan must be indicated what kind of configuration is required for project activities, in addition, major activities have to be planned with start and end dates.

Second deliverable is the configuration plan, which is the output of check phase. All project requests are collected and aligned with the existing configuration and regularization plans, if required, a new configuration (regularization) plan is proposed.

In commit phase takes place the macro allocation meeting, where the configuration plan and resource allocation are reviewed. The output of this meeting is the macro allocation plan, where resources are allocated for each sufficient project request.

The macro allocation plan, which also includes the configuration and regularization plan, is finally passed to operational level requests.

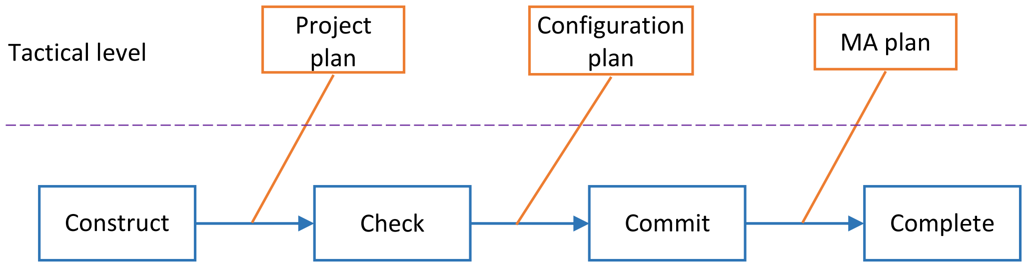


Figure 4-5.4C tactical level deliverables

Process authority and responsibility domains

Casavant & Kuhl (1988) consider authority and responsibility as fundamental components of the decision making process. Moreover, the authors make the difference between distributed and decentralized scheduler. While in distributed system the responsibility is distributed and authority is centralized, in decentralized systems both authority and responsibility are distributed.

Therefore, the scheduler in the suggested process has a distributed role that is performed by the consumers themselves. This means that responsibility for gathering information and carrying out policy decisions is distributed to the consumers, these are the project managers, while authority is centralized in DTE project and group lead.

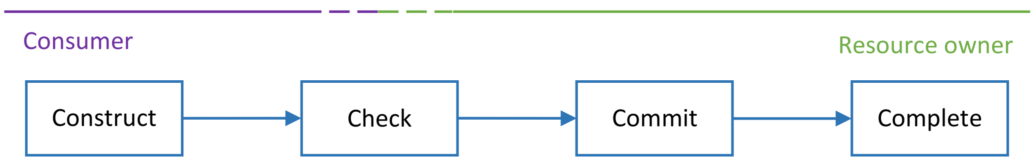


Figure 4-6.4C tactical level authority and responsibility domains

Project managers as consumers create and submit their project plans to the resource owner, when a resource is required. Then the resource owner, i.e. DTE project lead, takes the initiative and carries out the configuration management and hosts the macro allocation meeting. Ultimately, after the commit phase, if resources are dedicated to projects, the project managers become the resource owners for these resources on operational level.

4.3.3 4C process on operational level

Process deliverables

In the first step each consumer is required to describe what activity is going to be performed and what are the requirements regarding time and configuration. The deliverable of construct phase is a single request form. During check all new requests are aligned with the already existing one, the output of this phase is a TB utilization plan.

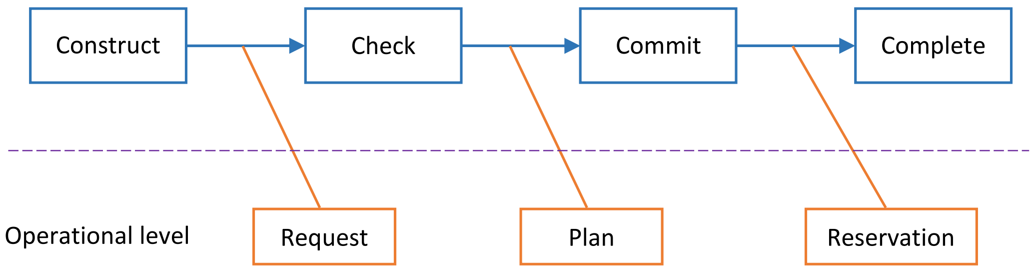
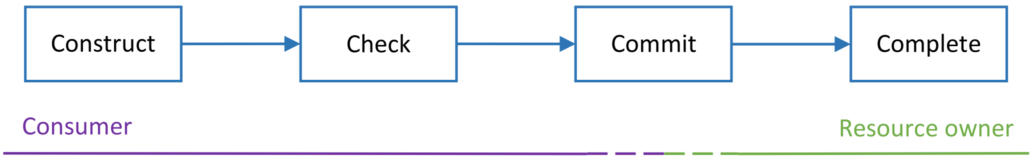


Figure 4-7. 4C operational level deliverables

If there are no conflicts or unexpected events and everybody commits to the plan, each request becomes a reservation. Final step of the process is when reservations are completed.

Process authority and responsibility domains

On operation level, the consumers are test engineers or anybody else, who requests to use a testbay. The decision making here is further distributed and consumers carry out the responsibility for the schedule generation. Once a schedule is generated and submitted, resource owners have to commit and approve it. The authority is centralized in project leads, however, if resource are not allocated to projects, DTE leads remain resource owner and they have the authority.



5. Design evaluation

In this chapter we evaluate the design based on the preset objectives and stakeholder needs.

5.1 Evaluation based on the objectives

In the begging were given three key objectives and three sub-objectives. The key objectives were: (1) to maintain the effectiveness level and increase the efficiency of resource utilization; (2) to introduce learning aspects that will help in future decision making; and (3) to provide flexibility in order to handle dynamic environment. The sub-objectives were: (1) standardized information; (2) reduced communication waste; and (3) reduced ad hoc decisions.

5.1.1 Effectiveness and efficiency

Effectiveness

Effective utilization of TBs corresponds to the proper allocation of resources to activities. Therefore, the main possible impact on effectiveness comes in the tactical level. The designed process makes small to no changes in the original process on this level. Rather, it describes, clarifies and puts a framework on the allocation process. Therefore, it is not expected the effectiveness level to be disturbed in a negative way by the designed process.

Efficiency

Two types of efficiency are considered – efficient scheduling, which measures the cost or effort to produce a schedule; and efficient resource utilization, which measures the resource idle time.

Efficient scheduling

The designed process contributes in multiple ways in boosting the efficiency and minimizing the effort for schedule generation. First and most important improvement is the better facilitation of decision making. The first step towards this made by clearly stating that decision making activities take place in the Check and Commit steps of the process (see section 4.3.1). Thus, the designed process restricts unnecessary decision making activities in the first and last steps. Secondly, the designed process describes the deliverables between each step, these are the desired outcomes that have to be achieved. In the case of the first step Construct, consumers are required to gather all relevant information for the decision making process before it starts. This ensures that no time will be lost for gathering of information after the first step. In addition, the requests are put in a standard format, which has a twofold contribution – (1) it assures that all necessary information is provided and (2) it helps for faster, even automated, processing of the information. Lastly, the designed process precisely describes the assignment of authority and responsibility in each step of the process.

Efficient resource utilization

In the objectives was given an efficiency rate of 70% for TB utilization. While the gathered data from the reservation system (see Appendix D: TBs utilization for 2013 and 2014) gives indication of a rising trend of utilization during the years, it has not to be mistaken with actual resource idle time. The currently used block scheduling policy predisposes for inaccuracy and respectively inefficiency. The designed process makes changes by reducing the granularity of blocks from an hour to a minute. By this adjustment, the designed process handles more efficiently requests that are shorter or not multiple of an hour. Therefore, the 4C process minimizes any time waste due structural restrictions. Resource idle time will be let to a minimum and fully dependent on the decision making steps and effectiveness goals.

5.1.2 Learning

The learning aspects of the designed process are currently scaled down to the gathering of information. Big set of data is the first step towards a learning process. The inbound data is unified in a structured format and new vital fields for the scheduling problem are introduced. The predictive strategy of the process is designed to assist the implementation of further learning algorithms that will relieve the stakeholders and contribute for the better decision making in future. For further discussion see 6.6 Limitations and recommendation for further improvements.

5.1.3 Flexibility

While most of the contribution of the designed process is on defining a structure, order and rules, which are all in contradiction with flexibility, it was not neglected. The first and biggest improvement regarding flexibility is the reactive strategy in place. This ultimately gives opportunity for changes in real time, when necessary. Second improvement is the introduction of block hierarchy and distributed authority and responsibility. For example, on operational level project managers have the authority to manage the resource in the best possible way for them. Third improvement towards flexibility is the reduced granularity of blocks. As mentioned before, this provides better accuracy and better meets the stakeholder needs. Lastly, the introduction of scheduling points and the release of unused resources in a fixed time points will give a chance for last minute scheduling.

5.1.4 Lean

The lean features in the face of information standardization and reduced waste time are in the core of the process and presented in every step. The two major changes in information standardization are the presentation of baseline schedule and its inputs on operational level, i.e. request form. The baseline schedule is structured and cleaned from unnecessary information. The request form also h standard format with relevant information only. All this contributes to clear information overview and transparency, which respectively decreases unnecessary communication between different stakeholders.

5.1.5 Ad hoc decisions

Ad hoc decisions occur in the Complete step and they are a result of either insufficient planning or unexpected events. The process aims to scale down to minimum ad hoc decisions due inaccurate decision making by utilizing the predictive strategy and the generation of baseline schedule. Thus, ad hoc decisions are limited to cope with unexpected events, which are unavoidable in the dynamic environment of R&D. This is implemented through the reactive strategy of the process, where activities that have to be rescheduled are pushed back in the process to the previous three steps of the process.

5.2 Evaluation based on stakeholder needs

For major stakeholder needs were identified through interviews in the beginning. Those are better information overview, better process control, better schedule stability, and better system functionality.

5.2.1 Information overview

The biggest contributors for better information overview in the designed process are the information transparency and accessibility. Information flow is clear and structured, and deliverables are standardized. In addition, this information is centralized in one place (the supporting system), which helps navigating through it. Secondly, information transparency is increased by the implementation of block hierarchy. This opens the allocation blocks to everybody to review what is occurring on a TB. Lastly, new vital information is presented to all stakeholders, e.g. real time TB operating status.

5.2.2 Process control

Better process control is achieved by delegating the role of resource owner to project managers on operational level. The block hierarchy contributes and facilitates this actions. In addition, the decision making on this level is distributed. This gives them the authority and flexibility to manage their allocated resources in the best possible way for them.

5.2.3 Schedule stability

Schedule instability is a result of ad hoc decisions and long term planning on operational level. As mentioned in section 5.1.5 rescheduling of activities are limited to the level of handling unexpected events. On the other hand, long term planning on operational level is restricted by the planning horizons. The designed process is a cyclic process that introduces scheduling points for a certain period of time in the future. Thus, rescheduling of activities due long span reservations is eliminated. Therefore, the majority of rescheduling activities will depend on the decisions made on tactical level.

5.2.4 System functionality

The designed process enables multiple improvements on the system functionality. However, there are few major enhancements and changes that stand out. First and most recognized is the reduced block granularity. This enables the capacity of reservations to be increased in tens of times. In addition, it also provides more accurate reservation time. The second big change is the introduction of scheduling hierarchy with distributed authority and responsibility. This helps managers and leads to manage work by themselves or to delegate this to their teams. Other improvements that are possible due the centralized data in the baseline schedule are the opportunities for reversed bottom-up search of resources and the implementation of notifications and reminders. The centralized data allows to search for a TB starting from the configuration requirements, instead of the current top-down way.

5.2.5 Stakeholders evaluation

The design was presented to the major stakeholders and they were asked to provided their evaluation. The stakeholders were separated on tactical and operational level.

Tactical level

In general, the stakeholders stated that the designed process is not so different than the current way of working. However, it is put in a framework and standardized. This is the result that was aimed to be achieved. As stated before, the old process was effective enough from the beginning but other parameters had to be improved. The designed process does not have a negative impact on the effectiveness. The introduction of planning and commitment horizons was welcomed. In addition, there was a suggestion for the implementation of penalties. These penalties are towards the consumers with allocated resources that are not able to fully utilize the resource. The suggestion was to open any not used time in the allocated block after the scheduling point passes. This could be seen as extra measure to motivate block owners to use efficiently their allocated time. In addition, it will decrease the communication between a resource owner and an external consumer. However, this could possibly have a negative impact on the flexibility of resource owners.

Operational level

Stakeholders on operational level stated that they see huge improvements on information overview, process control and system functionality. Two of the key features that they identified were the reverse approach in finding a resource and the ability to schedule activities on somebody's else name. In addition, they mentioned that they see increased schedule stability, but it was noted in a negative way that schedule stability is still highly dependent on higher management priority calls. There were also other remarks. First is that the process is focused on open TB scenarios, while in the majority of cases TBs are dedicated (allocated) to a project. Secondly, it was pointed out that volunteers are scheduled on Mondays, therefore, the scheduling point on operational level should be on Monday and not Wednesday. The next remark was addressed about the lack of setup configuration time in the current design. Lastly, it was stated that configuration management is absent.

6. Proposed scheduling process

6.1 4C process

The proposed scheduling process 4C is a uniform process that could be scaled up and down on tactical and operational level. It provides a structure to the current way of scheduling, describes the necessary activities and deliverables in a timeframe, and satisfied the stakeholder needs. It has lean and flexible properties and it facilitates the decision making by providing distributed authority and responsibility, and standardizes the necessary information.

Although represented in a line, the 4C process is a cyclic process that could be scaled based on macro and micro level scheduling points. In the current settings, one cycle on tactical level (monthly) corresponds to four cycles on operational level (weekly), see Figure 6-1.

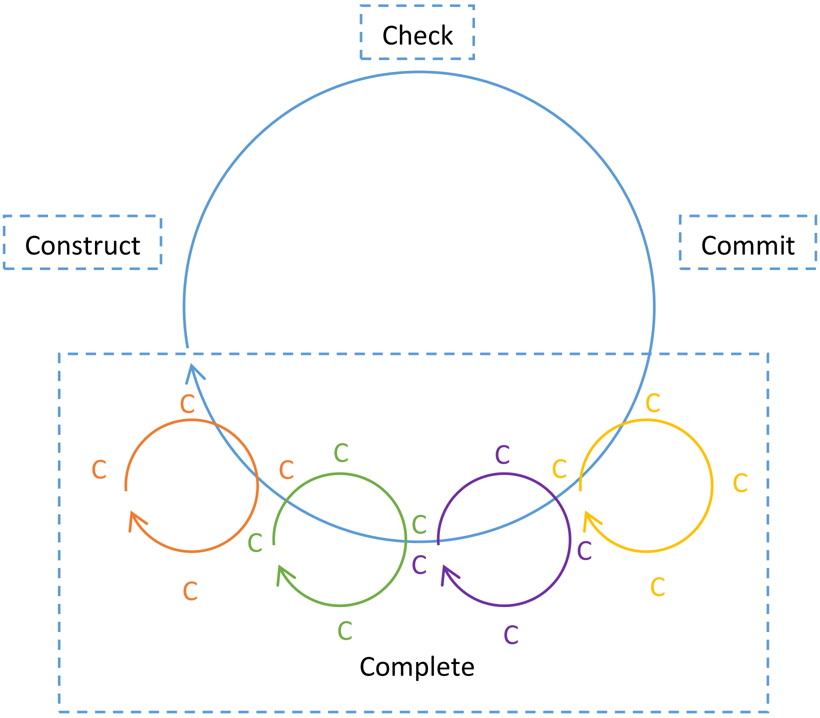
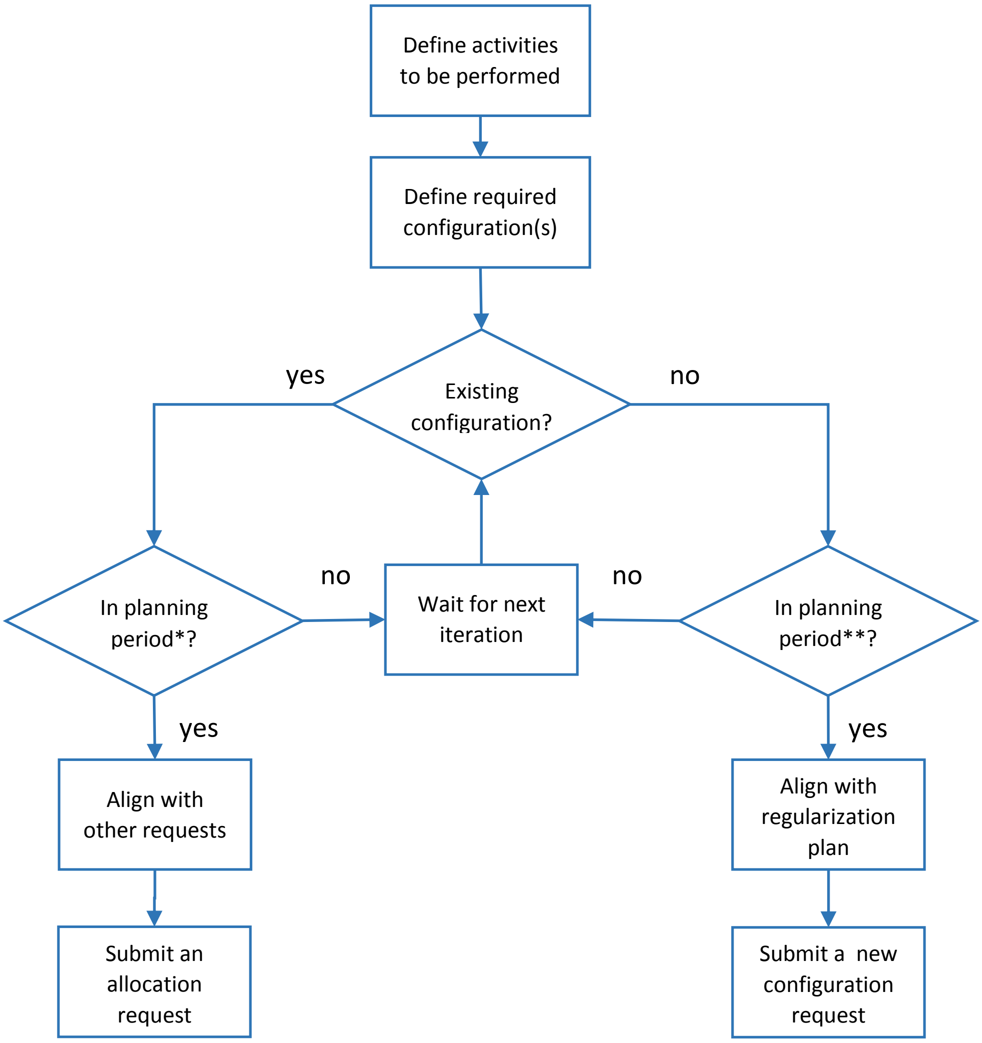


Figure 6-1 Cyclic representation of 4C process

6.2 Allocation procedure

The allocation procedure is a cyclic process that repeats on monthly basis. The (re)scheduling point is the currently existing macro allocation meeting.

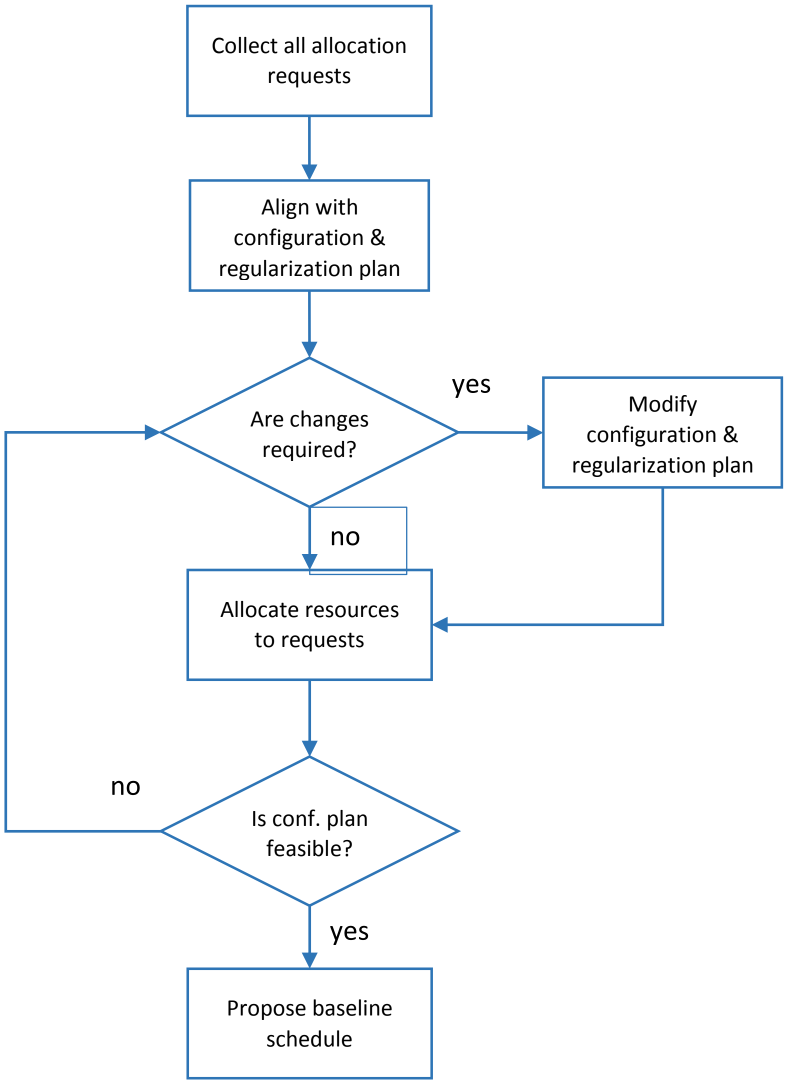
6.2.1 Construct



* Planning period(s) for existing configuration
** Planning period(s) for non-existing configuration

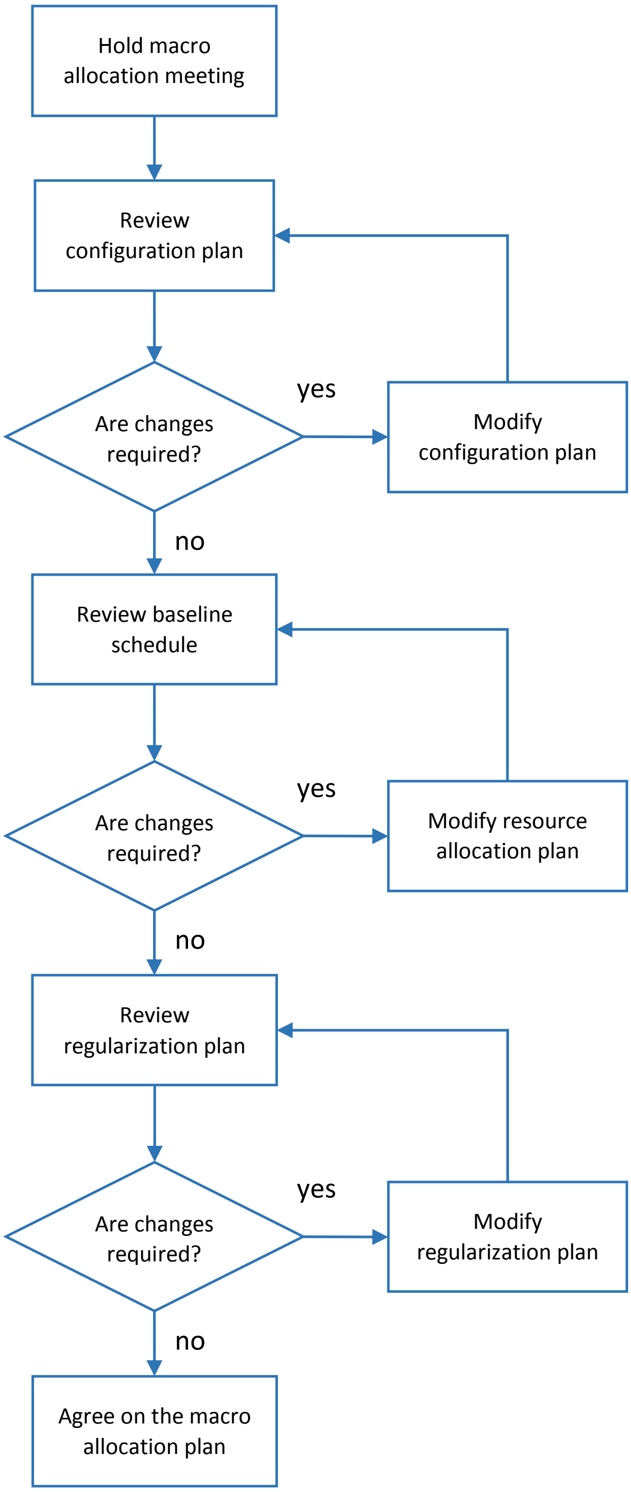
Project (program) managers are consumers that request resource allocation for their projects. In order to have a feasible allocation plan, they have to submit their request in the form of project plans, which contains configuration requirements and major activities plan with activity duration, start and end dates. In addition, project plans have to be aligned with each other as much as possible. By submitting these requests, they not only advocate for resource time for their projects, but also commit to use the resource in most efficient way. The requests are send in fashionable time manner, according to the planning horizon. Due the dynamic nature of R&D projects, it is required requests to be updated on monthly basis with the latest changes in projects' progress.

6.2.2 Check



In the second phase, the DTE project lead, acting as resource owner, collects all submitted requests and checks the current configuration plan. If changes are required, they are applied and a new configuration plan is created. Resources are allocated according to the requests and the configuration plan in the new baseline schedule. Once the predictive schedule is feasible the process goes to the next step.

6.2.3 Commit



The most important event in commit is the macro allocation meeting, where the resource owner and consumer meet and review the suggested configuration plan and time allocations. Any suggestions for updates or adaptions on the resource allocation are raised during this meeting. Once everybody in the meeting agree with the suggested plan, it is updated as macro allocation plan and visible to everybody else.

The macro allocation plan considers all resources and it consists of blocks assigned to different projects. If a resource is fully allocated to a single project, then it is dedicated resource. Blocks may overlap and the resource to be shared between two projects, but utilization must be lower or equal to 100%. In addition, in the case of more than two project claims for a particular resource or small claims lower than 20%, testbays could be left open and not allocated,

6.2.4 Complete

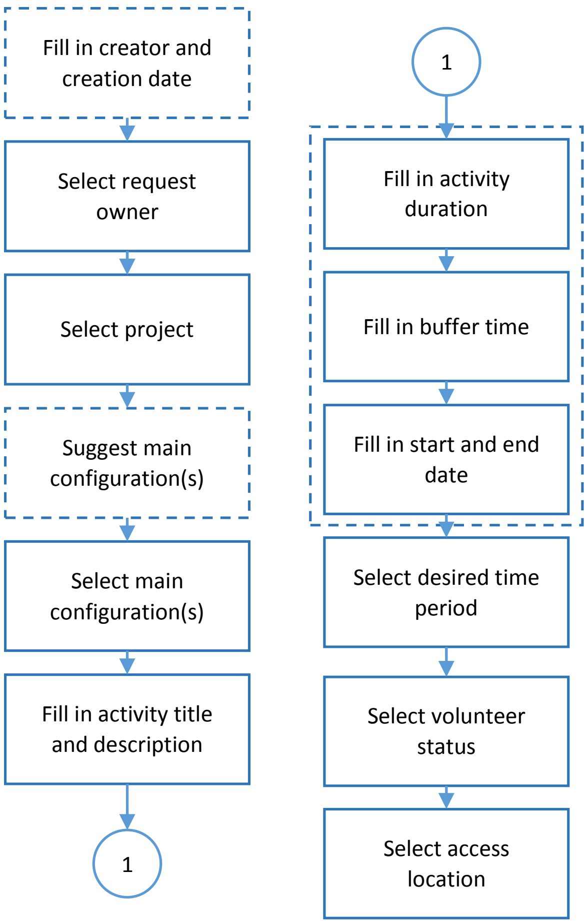
In complete the process starts on operational level. Project managers gain the authority for dedicated resources, while for open and shared resources, the resource owner remains the DTE project lead. This will give power to the project managers to better handle and utilize the given resources.

6.3 Scheduling procedure

With the introduction of the time horizons, the scheduling procedure completely shifts from dynamic to static scheduling. Based on the minimum requirements of one week planning in advance, the scheduling procedure becomes a cyclic process on weekly basis. Most of the similar cases in literature, such as (Fei et al., 2010), review the schedules on every Friday. However, due the limitation of one week requests for volunteers, a rescheduling of such tests becomes indisputably cancelations. Therefore, for a rescheduling day is suggested Wednesday. In this way, every consumer will have Monday and Tuesday to submit requests, if rescheduling of volunteer scans has to be done, next Thursday and Friday are still available options.

6.3.1 Construct

In the first phase of the process, consumers construct their requests. A standard form will guide the consumer through the required information. The main action in this step is information gathering, which means that the consumer does not even have to see the existing schedule. It is important to collect consumer desires towards system configuration and preferred time period, without the bias of the existing schedule. Due the block hierarchy, team leaders could also construct requests for their team members.



The following fields were identified as mandatory in the request form, many of which are already specified in the logging book form of the current way of working:

- Creator
- Request owner
- Project
- Main configuration parameters
  - System type
  - Field strength
  - Acquisition
  - Software version
- Time fields
  - Desired time period
  - Activity duration
  - Start date

    - End date
    - Buffer time
    - Creation date
- Activity title
- Activity description
- Volunteer status
- Access location
- Comment

6.3.2 Check

The main action during check phase is the decision making. In this step, the consumer aligns in time his/her request with other requests and existing reservations (discussed in next section). For first time here is indicated a concrete time slot of the request, while in previous step it was desired time period. The request bounds time wise to the existing plan.

In order to incorporate predictive mindset, overutilization of resources is allowed. The goal of this decision is to create an environment that captures possible conflicts in advance. Conflicts are solved by the resource owner in commit phase.

This conflict strategy could be very beneficial for fighting personalities, however, it may be very unfair for other. Therefore, a second technique is proposed for those, who are not willing to enter in conflict situation, due their calm personality, believe that it is a waste of time, or because of awareness that they have lower priority. Most flexible request, with large desired periods, and not schedule request could enter in an activity list. Very simplified activity list could work as a queue of tasks that wait for openings.

6.3.3 Commit

In commit phase, it is expected consumers to have submitted requests, by which, they have committed to them. However, the scheduling system is a two way stream and the resource owner has to review and approve these requests. In special cases for very important tasks or conflict situations, approval may come before the end of the commitment horizon. However, in the majority of cases when there are no conflicts, the resource owner commitment could automatically come at the end of the commitment horizon.

In the case of shared and open testbays, conflicts have to be arrange by the conflicting entities by using the escalation system described in section 3.2. No overutilization will be allowed after the commit phase, which means that all overlapping activities has to be resolved.

Once all requirements are satisfied, the requests become reservations as part of the schedule.

6.3.4 Complete

Complete is the last phase in the in the process. In this step consumers are responsible to indicate the activity start and end dates, and to update the comment section in reservation form in the case of machine failure or other unexpected event. If the activity is canceled due an expected event, the reserved time is freed and the activity list of waiting tasks is notified for the available opening.

6.4 Adjustments based on stakeholder evaluation

Two stakeholder suggestions were considered to be included in the proposed scheduling process. First suggestion was to implement a penalty to stimulate resource owners to better manage their activities. This is achieved by opening allocated time to external consumers. Although it will not be always possible a resource to be used by an external consumer, it will not be process wised restricted. The possible negative outcome of these penalties is that resource owners will over schedule activities. This is considered to be handled by being visible due the information transparency provided to all stakeholders. Second and minor suggestion was the scheduling point to be moved to Mondays, instead of Wednesdays. Since the scheduling point is mostly dependent on the requested volunteers, which happens on Monday, it will have no impact on other teams. Therefore, scheduling point could be moved on Mondays.

6.5 Recommendations for Implementation

The recommendations for implementations are organized in three options based on the business options of the business case guidelines presented in the project management methodology PRINCE2.

6.5.1 Do nothing

If no actions are taken, then there will be impact on the effectiveness and efficiency. From the gathered data of TB utilization for 2013 and 2014 (see Appendix D: TBs utilization for 2013 and 2014), it is clear that TB demand rises. If this trend continues, in matter of several years, the resources will not be just limited but scarce. This will have it consequences on the effectiveness of work. Both effectiveness and efficiency will start to decrease over time.

6.5.2 Do minimum

The minimum effort towards implementing the process designed is by using software off the shelves. Microsoft SharePoint is an environment that could facilitate the majority of system requirements. In addition, it could be easily coupled with Microsoft Outlook plugin for quick steps and easy access. The benefits of this implementation are the user friendly experience that is build-in in SharePoint, easy integration with other services and the easy maintenance. However, a drawback is the possibility of system functionality limitations, since SharePoint purpose is different.

6.5.3 Do something

In order the proposed process to be fully implemented and supported by a system more effort has to be put. Since it is nearly impossible to find a product that supports completely the system requirements, the system has to be custom build. This way, all functionality and features of the system could be developed. The benefits are obviously unlimited functionality and customizations. However, a major drawback is the significant difficulty to implement such a system. In addition, maintaining such a system could be even more costly.

6.6 Limitations and recommendation for further improvements

In section 4.1 was stated that proactive scheduling has the edge over predictive scheduling. Due multiple limitations proactive strategy was not possible to take place. Rather, predictive strategy was selected as best solution that will facilitate and prepare necessary conditions for a proactive strategy to take place in the future. A recommendation for further improvement is to monitor key performance indicators regarding the proposed process and when a sufficient amount of data is gathered to migrate to a proactive-reactive strategy. The ultimate solution will be a completely proactive strategy.

During defining the scope of the problem configuration management of resources and setup considerations were excluded. However, as stakeholders mentioned in their evaluation there are a lot of possible improvements towards better, faster and easier configuration management. The recommendation is that focus should be put on this area, after the proposed scheduling process is at place. The configuration management process should be supported by a separate system that will work together with the scheduling system for delivering best performance.

7. Conclusion

In this thesis we investigate a business process challenge in Philips Healthcare's MRI R&D department. The main research goal was to design a process that effectively and efficiently utilizes the limited resources of the development test environment. In order to achieve this, we answer two main research questions with few sub-questions each. The first research question was towards the theoretical domain, while the second was about the practical solution of the problem. Here we provide brief answers to those questions.

SQ1-1: What are the fundamental elements and basic principles of scheduling defined in the literature?

We reviewed the academic literature, in order to get familiar with the scheduling terminology and concepts. The basic scheduling system is explained. It consists of three roles – a consumer, a scheduler and a resource, where the scheduler is the intermediate actor. If the process is initiated by the consumer than the action is called task scheduling, while if it starts from the resource it is called resource allocation. Next are reviewed the scheduling environments and models for these environments. These are the deterministic and stochastic environments and the three models to schedule in this environments – offline, online, and hybrid scheduling. Finally, the most popular priority rules are investigated in the form of scheduling policies.

SQ1-2: What similar cases could be identified in the literature?

Two problems in the scientific literature were identified that match the current settings. The first and most identical is the stochastic resource-constrained project scheduling. Similar cases were found in the field of pharmaceutical and agricultural research and development processes. The development of new chemical products meets very similar unexpected events to the one experienced during the development of complex MRI systems. In addition, both sectors are highly regulated and extensive testing is required.

The second similar problem is the operating room scheduling problem. It was considered due the fact that it also tackles with significant amount uncertainties. In addition, effectiveness and efficiency play the most important role for the saving of people's lives.

RQ1: What scheduling concepts could be identified in the literature and what are their advantages and disadvantages?

The stochastic and hybrid concepts were selected as best solutions to the current challenge. The pure stochastic approach minimizes significantly the makespan of the project, however, it requires a lot of computational power and time, in order to solve more complex problems. In addition, it needs a significant amount of historical data to operate with high accuracy.

The hybrid concepts consist of some estimations about the uncertainties and the means to cope with them. There are two hybrid approaches – predictive-reactive and proactive-reactive. The difference between both is that the predictive strategy estimates possible disruptions but acts only when they occur during execution, while the proactive strategy handles the uncertainty before they occur. The predictive-reactive strategy is capable of handling complex scheduling problems, but it is not an optimal solution. Whereas the proactive-reactive strategy is the balanced solution between complexity and optimality.

SQ2-1: How the scheduling of DTE resources is currently done?

The scheduling concept that is used in the current situation is close to the predictive-reactive one. However, the baseline schedule is mostly deterministic with less focus on uncertainty. This puts more weight on the reactive actions, which leads to instability in the baseline schedule.

Through interviews, observations and documentation, it was possible to map the current scheduling process. The flow chart enabled two major bottlenecks to be identified in the process both due a loss of information transparency horizontally and vertically in the organization. In addition, it was identified that only some part of the process is handled by the current reservation system, which holds in place the information visibility throughout the process.

SQ2-2: How stakeholders perceive the current DTE reservation process?

The main stakeholders were interviewed in order to understand their perception towards the scheduling process. They indicated that they like the openness of the reservation process for everyone to reserve time and the information that is provided by the reservation system. During the interviews it was possible to identify that each stakeholder sees the process in slightly different way, which suits their needs best. They came with four possible directions for further improving the scheduling process – better information overview, better process control, better schedule stability and better system functionality.

RQ2: How to improve the current scheduling procedure by using scheduling concepts with regards to stakeholders' complaints and desires?

Based on the current scheduling procedure a new process was designed that fits both literature findings and stakeholders' needs and complains. The new process utilizes the predictive-reactive concepts as the current procedure, but it incorporates several new enhancements. Modified block scheduling strategy with block hierarchy and smaller granularity is suggested to handle under-utilization, increase in visibility and also to give decentralized authority for the most efficient use of the resources. Next, the information across the whole process from tactical to operational level is standardized. Fixed scheduling points are suggested, in order to have recurrent scheduling periods that brings focus to the short-term tasks on operational level. In addition, a new concept of commitment periods is introduced to give authority to lower levels and reduce escalations. Finally, the process states what are the goals for each step and what actions are to be taken.

SQ2-3: What are the perspectives for the new scheduling process to improve the way of working?

The process designed was presented to the stakeholders and evaluated based on their opinion and the initial objectives of the research. Overall, stakeholders saw the benefits of these changes to the current process on each of the main and sub-objectives and they considered them as improvements.

Based on the positive design validation, the proposed process could be considered as viable improvement to the current way of working. The simplicity behind the process makes it easily adaptable by the stakeholders, in addition to a low cost implementation. Although it is not an optimal solution, the proposed process has all necessary prerequisites to support such solution in the future. Therefore, it is highly recommendable for the management team to proceed with the implementation of this process in their organization.

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Appendix A: Scheduling policies

Method	Description	Author	Advantages	Disadvantages
First-come, first-served (Open)	The first person who requests a time slot, receives it.	(Breslawski & Hamilton, 1991)	• Ease of scheduling • Simple to implement • Better flexibility than blocking	• Idle time, due task cancellation • Overtime • Overbooking • High cancellation rate • Frictions • Highly variable utilization rates • Generally low utilization rates
Blocking	A person receives a specific block of time and have full control of it.	(Breslawski & Hamilton, 1991)	• Better overall use of rooms • Reduced competition • Reduced administrative work • Known start times • High satisfaction of users with heavy use needs • Guaranteed start times • Ease of scheduling • Better resource utilization in the afternoon than FCFS	• Holding blocks while not needed • Blocks are often left unscheduled due poor use • Idle time, due short rescheduling notice • Difficult to handle emergencies, due to unleveled work
Dynamic block	Each person's block use is reviewed on regular basis and adjustments are made for future (reduced time).	(Breslawski & Hamilton, 1991)	• Less unused time than blocking • Better resource utilization than blocking and quarter day sessions	• Higher risk for overtime
Longest time first	The earliest time slots are allocated to the longest procedures, followed by shorter procedures.	(Breslawski & Hamilton, 1991)	• Handles high variability tasks first, which gives time to react and shift other tasks to do all on time • Decreased chance for large overruns at the end of the scheduled day • Highest resource utilization compared to STF and FCFS • Lowest overtime compared to STF and FCFS	• Higher mean completion time than STF (higher lead time) • Specific tasks are always prioritized • Emergencies cause large inefficiencies
Shortest time first	The earliest time slots are allocated to the shortest procedures, followed by longer procedures.	(Breslawski & Hamilton, 1991)	• Lower mean completion time than LTF (shorter lead time)	• Lower flexibility in rescheduling • Poor resource utilization • Large amount of overtime • Higher throughput
Top-down, bottom-up (Modified block)	A day is divided in two - in the first half, long cases are scheduled according to FCFS, and in the second	(Breslawski & Hamilton, 1991)	• Handles idle time • Handles potential overtime problems when they can still be solved	• Lower probability (for later cases)

	half, short cases are scheduled (FCFS).			
Quarter day sessions	A variation of block scheduling with block size restriction – 4 blocks per day each for different person or emergence buffers.	(Breslawski & Hamilton, 1991)	• (same as blocking) • Better resource utilization in the afternoon than blocking	• (same as blocking) • Regular monitoring of resource usage • Revisions of time allocation
Multiple-room system	The person rotates among the rooms after each task.	(Breslawski & Hamilton, 1991)	• Eliminates waiting for setup/cleanup time • Decreased overtime for supporting staff	

Appendix B: Product Realization Process Structure

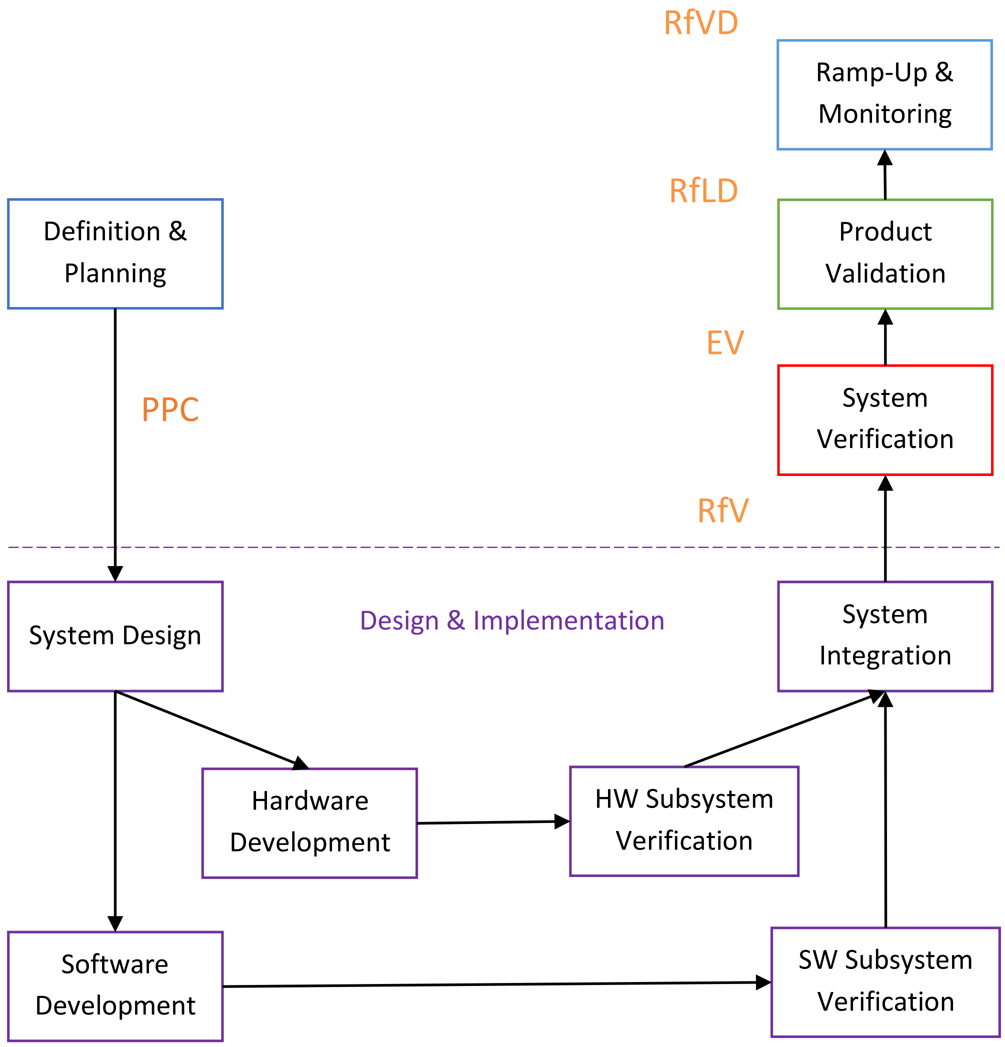

Figure B-0-1. Section of PRP (V model)

The Product Realization Process (PRP) describes the development of a (new) product with a multi-disciplinary team with all relevant stakeholders involved. It's a time-driven process and is based on a defined process (Standard V Model) as agreed in Philips Healthcare. This process has several phases with NPI milestones as key controls between each phase. On the diagram above is illustrated only the most relevant part of the PRP process with regards to DTE reservation process.

Phases:

- Definition & Planning – The detailed product/system requirements and the global design are defined. Detailed project plan, including interfaces with internal and external partners, is made. The phase ends with Project Plan Commitment (PPC) milestone.
- Design & Implementation – After the PPC milestone the project starts the design with a multidisciplinary team in the Design and Implementation phase resulting in a product on module level including integration to next level. Next the project is divided in two streams: hardware and software development. For each stream subsystem verification starts during development and when it is done both streams combine in system integration.
- Verification - System verification can start after a Release for Verification (RfV) milestone is reached. During this phase is verified the technical specifications of the system using a production equivalent product.
- Validation & Transfer - Product/Clinical Validation starts after End of Verification (EV) milestone and finishes with Release for Limited Delivery (RfLD) milestone. The product is validated according to the intended user requirements. In addition, it is validated also the production process, initial transfer to production, sales & service and support.
- Ramp-Up & Monitoring – During this phase the product is followed during a predefined period to debug and improve, create the feedback loop from customer service and development communities.

Tests distribution during PRP

In the PRP structure is seen a clear separation between different phases and activities, however, in practice some of the activities may overlap but the milestone are a hard stop (fixed barriers indicating the end of a phase). For example, some of the design and implementation teams use agile methodology, which means that they do short iterations of design, development and subsystem testing. This means that they may require testing on DTE test machine prior development is complete. This could be the reason why there are no milestones during development & implementation phase. The same applies for the other groups; a hypothetical tests distribution could be seen on fig.2. System verification team needs to run pre-verification tests before RfV and product validation, application and service team needs to do pre-validation tests prior EV. This parallel way of working requires strong coordination between teams in order to share the limited amount of test machines.

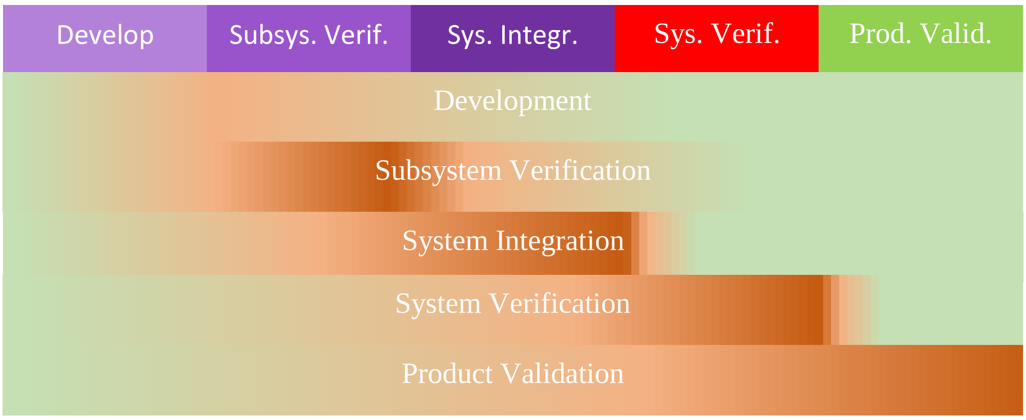

Figure B-0-2. Hypothetical tests distribution during PRP (heat map)

Appendix C: Stakeholder analysis

After the first iteration of the stakeholder mapping were identified 21 process-level stakeholders and 6 system-level stakeholders. It is known that the list of process-level stakeholders is not complete and some of the information for the current stakeholders is not yet defined.

Business / Process-level Stakeholders

Process-level stakeholders are physical stakeholders who are involved across the complete reservation process. They are divided in two major groups: outside and inside Product Realization Process (PRP) (TBD identify NPI stakeholders). The list consists mainly of stakeholder groups (by department/purpose) and it has to be broken to individual roles. In addition, the stakeholders have to be mapped in a grid according to their organization power. The key stakeholders have the most organization power or they are involved at most in the reservation process.

Table C-0-1. Business stakeholders

Key	Group	Role	Description
Outside PRP			
	Ambient Lighting		Ambient Lighting creates calm and relaxed atmosphere for patients, in addition to the aesthetics view.
X	Applications and Trainings		The Clinical Applications Team of the BU MRI acts as the representative of the end user towards the different stakeholders in BU MRI. It safeguards the clinical usefulness of our product offerings as tools for diagnostic decision making.
	Clinical Science		TBD
	Course and Personal Education		Every employee with access to DTE takes a MR safety course. In addition every employee can reserve a test machine for personal education.
	Customer Excellence		Customer Excellence or Life Cycle Management maintains the product through its production live cycle while retaining form, fit and function.
X	Customer Visits	Coordinator/Lead	Planning live scanning for customer visits.
X	DTE	Engineers	Responsible for the maintenance of MR test systems.
X	DTE	Group Lead	Responsible for the organization of work – workflows, resources (amount of different configurations), planning.
X	DTE	Project Lead	Responsible for the quality and functionality of test machines. Arranging materials needed for test machines. Managing capacity of DTE engineers. Hosts the macro allocation meetings.
	Manufacturing		Test installations.
	Photo Shoots		Photo shoot sessions for different purposes.
X	PMO	Project Management Director	Responsible for cross-project priority calls for using test machines according to program priorities.
Inside PRP			

X	Development	Hardware Project Lead	Create high level hardware development plans and manages development groups. Requests macro allocation time.
X	PMO	Program Manager	Create high level program plans and manages workflow. Requests macro allocation time.
X	Development	Software Project Lead	Create high level software development plans and manages development groups. Requests macro allocation time.
X	Service Innovation	Lead	Creates service information manual for field service engineers – installation instructions and fault finding.
X	Development	Software Group Lead	Plans and manages software development. Requests micro allocation time.
X	Subsystem Verification	Lead	Plans and manages subsystem verification testing. Requests micro allocation time.
X	System Integration	Lead	Plans and manages system integration testing. Requests micro allocation time.
X	System Verification	Lead	Plans and manages system verification testing. Requests micro allocation time.
X	Clinical Validation	Lead	Plans and manages system validation testing. Requests micro allocation time.

System-level Stakeholders

System-level stakeholders are immaterial stakeholders that are interested in certain software aspects and concerns, and are involved in the project as a lobby to these aspects.

Table C-0-2. System stakeholders

Key	Group	Role	Description
X	Architecture		TBD
X	Maintainability		TBD
X	Privacy		TBD
X	Reliability		TBD
X	Scalability		TBD
X	Usability		TBD

Stakeholder interviews

Short Interview with Key Stakeholders

1. Short Introduction
2. Questions:
   a. Could you describe what is your role and how DTE is connected to your work?
   b. What helps you do your job in the reservation process/system? What would you keep the same?
   c. What possible improvements do you see in the reservation process/system? What would you like to change?
3. Summary of other opinions

Appendix D: TBs utilization for 2013 and 2014

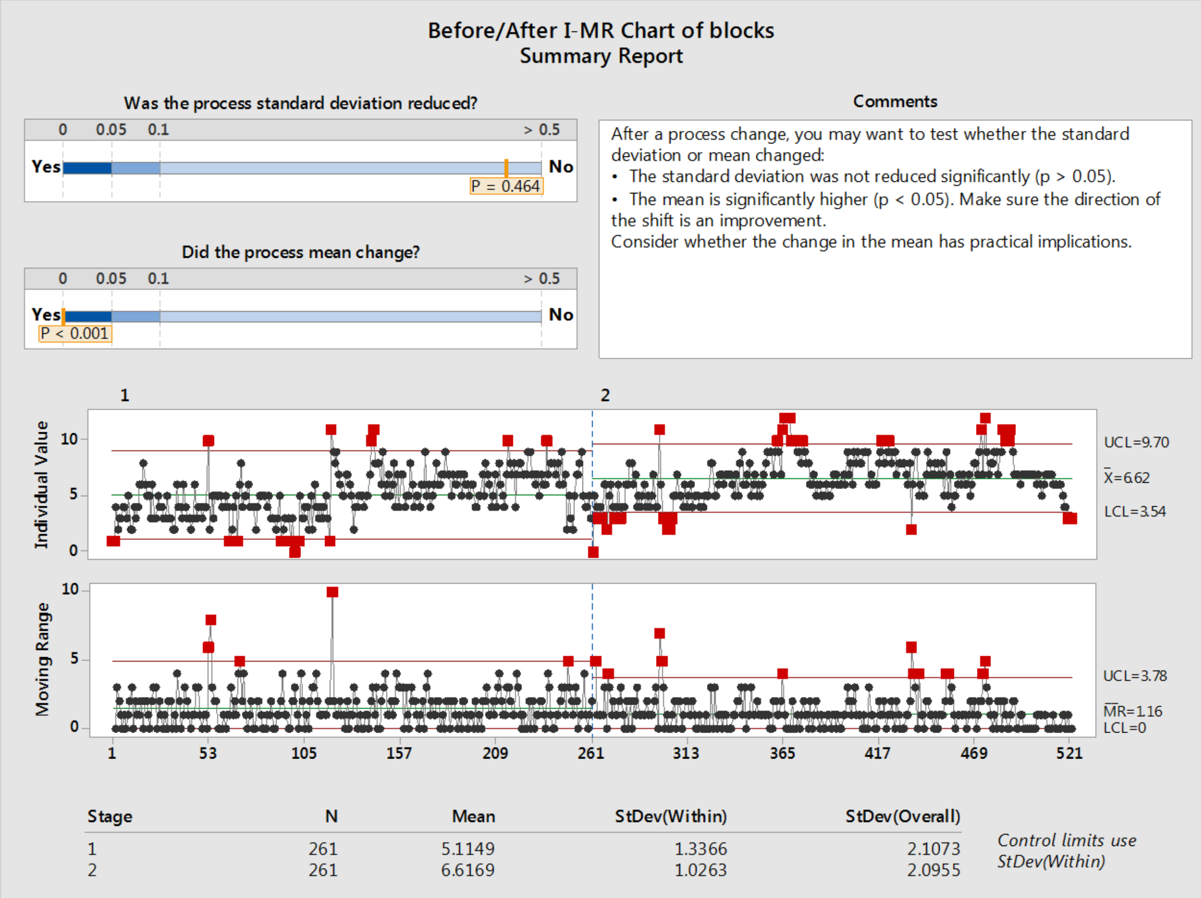

Figure D-0-1. I-MR analysis on TB reservations

Stage – 1 – 2013; 2 – 2014 N – Work days Mean – average hours per day (10 hours)

I-MR analysis on reservations for all TBs made between 08:00 and 18:00 during work days for 2013 and 2014.

First visible change in 2014 is the increased amount of reservations on average, which directly represents utilization:

	2013	2014
TB utilization	51.1% (5.11 hours/work day)	66.1% (6.61 hours/work day)

Second visible trend is the growth of reservations in each year:

	2013		2014	
	1st half	2nd half	1st half	2nd half
TB utilization	~40%	~60%	~50%	~75%

Appendix E: Scheduling problem

Request properties – Job characteristics

Each request has common properties, such as owner, setup time, processing time, buffer time, start-end dates, priority level, description, project relations, configuration requirements, volunteer scanning, remotely controlled and other. Currently, in the system are visualized only the scheduled start-end dates, description, owner, and project relation. Setup time is either placed as a second activity prior the main activity, or similar to buffer time, which is not indicated. Priority level is a complex parameter that is dependent on the project priority, but also on the test priority inside the project, which makes it hard to quantify. Another type of information that is not visible, however, always asked before a discussion for scheduled activity, are the actual configuration requirements for the test and volunteer scanning. For NPI projects volunteer scanning is performed mainly at the end of the development process during validation and it gives weight to the scheduled activity, if the volunteers are already planned, which is done a week before the actual test.

Depending on the job there are three main group of configuration requirements:

- Any configuration
- Main configuration – depends on the magnet type
- Specific configuration – depends on specific installed hardware and/or specific software version

Testbay properties – Machine environment

On operational level the machine environment is defined by the configuration plan and it has three cases. The first one is a single machine environment, where a set of jobs need a specific configuration that is planned on a single machine. The second and third case are when more than one machine satisfies the requirements of the job, then the machine environment is either identical machines in parallel or semi-identical that need small setup.

A test bay configuration is defined first by its hardware configuration and then by its software. There are 3 main hardware systems with 13 different variations in total. In addition, testbays distinguish what type of hardware is installed. There are customer bays that are built with production parts and there are engineering bays that hardware parts could be still in development. Each machine can support different software versions that are installed on separate computers (2-4 on a testbay). Software versions vary and there are more than 20 options, when switching between them setup time may vary from minutes (switching the computer) to couple of days (full system adjustments).

Restrictions and constrains

The restrictions and constrains that apply to the schedule processing are:

- Release dates – the majority of tasks could be started in a certain point of time.
- Preemptions – very small part of tests could be stop once they started and start later from the same moment, but duo the clustering of tests in blocks it could happen.
- Precedence constraints – most of the PRP projects tests are chained. In addition there are relations between different projects that require some activities to be performed first.
- Sequence dependent setup time - since most of the tasks need detailed specific configuration and there are 17 available machines and 13 main configurations multiplied by tens of software version, setup time between job is unavoidable

- Job families – activities are part of projects, but also there are similar activities in each project
- Breakdowns – in R&D environment breakdowns are undesirable but possible
- Machine eligibility restrictions – some machines are not allowed to be modified, e.g. customer bays, but other identical machines (engineering bays) are allowed to be modified
- Recirculation – same job could be repeated, if the results of the first time are not satisfying

Objective functions

The objectives that have to be minimized are:

- Makespan
- Total idle time / Underutilization
- Number of cancelations
- Throughput
- Throughput of weighted jobs
- Waiting time