UNIVERSITY OF PANNONIA

DOCTORAL THESIS

Matrix-based project planning method for multi-level project environments

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Abstract

Doctoral School in Management Sciences and Business Administration
Department of Quantitative Methods

Doctor of Philosophy

Matrix-based project planning method for multi-level project environments

by Gergely Lajos NOVÁK

Flexible methods, such as agile, hybrid and extreme project management, are increasingly replacing traditional project management. The popularity of flexible approaches is growing significantly in non-software areas as well. Only a few methods, however, can address projects of a flexible nature, and no project databases or topological, time-, or resource-related indicators are available in the literature.

To represent the different types and attributes of project plans, such as individual and multiple projects, programs, single- and multiple execution modes and demands, this study proposes a unified matrix-based model (UMP). Using the model, a compound matrix-based project database (CMPD) is constructed that combines 15 existing heterogeneous project and multiproject libraries from the literature, including 32 datasets, both artificial and real-life data, with the ability to support flexibility.

A flexible structure generator (FSG) is also proposed to generate supplementary tasks and flexible dependencies using a specified parameter and to analyze the effects on project databases. Topology and demand-related indicators were adapted, and new indicators were proposed to address flexibility. A case study for a software development multiproject plan from the automotive industry was used to validate the model and the corresponding parameters.

Using correlation graphs, the relations between structure- and demand-related indicators were analyzed. Comparing the simulated and real-life databases revealed the contrast in indicator value ranges, that can be improved with flexibility. Indicators show that flexibility decreases complexity and serial execution with lower project duration and higher resource demands. Decisions in the planning phase can be significantly improved by considering minimal and maximal (demand) structures generated by the FSG. Using metaheuristic optimization, the different flexible structures were solved to near-optimality. The constructed open database allows users to test both traditional and flexible project scheduling algorithms.

Keywords: Multilevel project management; Project database; Flexibility; Topology, Time- and resource related indicators

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Zusammenfassung

Doctoral School in Management Sciences and Business Administration
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Doctor of Philosophy

Matrix-based project planning method for multi-level project environments

von Gergely Lajos NOVÁK

Traditionelles Projektmanagement wird zunehmend durch flexible Methoden wie agiles, hybrides und extremes Projektmanagement ersetzt. Auch in Nicht-Software-Bereichen nimmt die Popularität flexibler Ansätze deutlich zu. Allerdings können nur wenige Methoden Projekte mit flexiblem Charakter adressieren, und in der Literatur sind keine Projektdatenbanken oder topologische, zeit- oder ressourcenbezogene Indikatoren verfügbar.

Um die verschiedenen Typen und Attribute von Projektplänen, wie Einzel- und Mehrfachprojekte, Programme, Einzel- und Mehrfachausführungsmodi und Anforderungen darzustellen, schlägt diese Studie ein einheitliches Matrix-basiertes Modell (UMP) vor. Unter Verwendung des Modells wird eine Verbundmatrix-basierte Projektdatenbank (CMPD) konstruiert, die 15 kombiniert vorhandene heterogene Projekt- und Multiprojektbibliotheken aus der Literatur, einschließlich 32 Datensätze, sowohl künstliche als auch reale Daten, mit der Fähigkeit, Flexibilität zu unterstützen.

Außerdem wird ein flexibler Strukturgenerator (FSG) vorgeschlagen, um ergänzende Aufgaben und flexible Abhängigkeiten anhand eines vorgegebenen Parameters zu generieren und die Auswirkungen auf Projektdatenbanken zu analysieren. Topologie- und nachfragebezogene Indikatoren wurden angepasst und neue Indikatoren wurden vorgeschlagen, um die Flexibilität zu adressieren. Um das Modell zu validieren und den entsprechenden Parametern wurde ein Softwareentwicklungs-Multiprojektplan aus der Automobilindustrie in einer Fallstudie verwendet.

Anhand von Korrelationsgraphen wurden die Beziehungen zwischen struktur- und nachfragebezogenen Indikatoren analysiert. Der Vergleich der simulierten und realen Datenbanken zeigte den Kontrast in den Wertebereichen des Indikators, der durch Flexibilität verbessert werden kann. Indikatoren zeigen, dass Flexibilität die Komplexität und Serienausführung verringert, mit kürzerer Projektdauer und höherem Ressourcenbedarf. Entscheidungen in der Planungsphase können durch die Berücksichtigung minimaler und maximaler (Bedarfs-)Strukturen, die von der FSG generiert werden, erheblich verbessert werden. Mittels metaheuristischer Optimierung wurden die verschiedenen flexiblen Strukturen nahezu optimal gelöst. Mit der konstruierten offenen Datenbank können Benutzer sowohl herkömmliche als auch flexible Projektplanungsalgorithmen testen.

Stichworte: Mehrstufig Projektmanagement; Projektdatenbank; Flexibilität; Topologie, Zeit- und ressourcenbezogene Indikatoren

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List of Abbreviations

ANOVA	**an**alysis **o**f **va**riance
GA	**g**enetic **a**lgorithm
MPE	**m**ulti-**p**roject **e**nvironment
AoN	**a**ctivity **o**n **n**ode
AoA	**a**ctivity **o**n **a**rrow
CPM	**c**ritical **p**ath **m**ethod
PERT	**p**roject/program **e**valuation and **r**eview **t**echnique
GERT	**g**raphical **e**valuation and **r**eview **t**echnique
eEPC	**e**xtended **e**vent-driven **p**rocess **c**hains
CCPM	**c**ritical **c**hain **p**roject **m**anagement
mPm	**m**etra **p**otential **m**ethod
pDm	**p**recedence **d**iagramming **m**ethod
WBS	**w**ork **b**reakdown **s**tructure
PM	**p**roject **m**anager
MCS	**M**onte-**C**arlo **s**imulation
SDP	**s**oftware **d**evelopment **p**roject
IT	**i**nformation **t**echnology
ICT	**i**nformation and **c**ommunications **t**echnology
PSP	**p**roject **s**cheduling **p**roblem
RCPSP	**r**esource-**c**onstrained **p**roject **s**cheduling **p**roblem
RCPSP-AS	**r**esource-**c**onstrained **p**roject **s**cheduling **p**roblem with **a**lternative **s**ubgraphs
RCPSP-AC	**r**esource-**c**onstrained **p**roject **s**cheduling **p**roblem with **a**lternative activity **c**hains
RCMPSP	**r**esource **c**onstrained **multip**roject **s**cheduling **p**roblem
MMRCPSP	**m**ulti**m**ode **r**esource **c**onstrained **p**roject **s**cheduling **p**roblem
MMRCMPSP	**m**ulti**m**ode **r**esource **c**onstrained **m**ulti**p**roject **s**cheduling **p**roblem
PSPLIB	**p**roject **s**cheduling **p**roblem **lib**rary
MNPG	**m**ulti-**n**etwork **p**roblem **g**enerator
EF	**e**arliest **f**inish
ES	**e**arliest **s**tart
LS	**l**atest **s**tart
LF	**l**atest **f**inish
EST	**e**arliest **s**tart **t**ime
EFT	**e**arliest **f**inish **t**ime
LST	**l**atest **s**tart **t**ime
LFT	**l**atest **f**inish **t**ime

SST	**s**cheduled **st**art **t**ime
F-S	**f**inish-to-**s**tart relation
GPR	**g**eneralized **p**recedence **r**elation
TPT	**t**otal **p**roject **t**ime
DSM	**d**esign **s**tructure **m**atrix
DMM	**d**omain **m**apping **m**atrix
PDM	**p**roject **d**omain **m**atrix
PEM	**p**roject **e**xpert **m**atrix
LD	**l**ogic **d**omain
TD	**t**ime **d**omain
CD	**c**ost **d**omain
RD	**r**enewable resource **d**omain
ND	**n**onrenewable resource **d**omain
QD	**q**uality **d**omain
DSDM	**d**ynamic **s**ystems **d**evelopment **m**ethod
CMPD	**c**ompound **m**atrix-based **p**roject **d**atabase
UMP	**u**nified **m**atrix-based **p**roject-planning **m**odel
FSG	**f**lexible **s**tructure **g**enerator
M^4	**m**atrix-based **m**ulti-level **m**ulti-**m**ode
NPD	**n**ew **p**roduct **d**evelopment
AHP	**a**nalytical **h**ierarchy **p**rocess
R&D	**r**esearch and **d**evelopment
CLD	**c**ompact **l**etter **d**isplay
CV	**c**oefficient of **v**ariation
CD	**c**oefficient of **d**ispersion
LOB	**l**ine of **b**alance
TPM	**t**raditional **p**roject **m**anagement
APM	**a**gile **p**roject **m**anagement
HPM	**h**ybrid **p**roject **m**anagement
xPM	e**x**treme **p**roject **m**anagement
MPx	emertxe **p**roject **m**anagement (⟵)
WIP	**w**ork **i**n **p**rogress
RQ	**r**esearch **q**uestion
RA	**r**esearch **a**ssumption
RT	**r**esearch **t**hesis

List of Symbols

Latin symbols

$a_i(T)$	scheduled execution time interval of task a_i
a_i	task i
D	maximal number of short arcs
EF_i, LF_i	early and late finish for task i
ES_i, LS_i	early and late start to task i
$f\%$	rate of flexible dependencies
fp	flexibility parameter, the ratio of flexible dependencies and prioritized tasks to all tasks and dependencies
FS_i	free slack of task i
k	number of task completion modes
$L(i_1, i_2)$	length of an arc between tasks i_1 and i_2, i.e., the difference between their progressive level numbers
$\overrightarrow{L}$	longest (critical) path
$l_{ij} = [\mathbf{LD}]_{ij}$	element of the logic domain, task occurrence if $i = j$, and arc that represent the precedence relation between tasks i and $j \neq i$ (in this case, $l_{ij} = 1$ means task i precedes task j)
n	number of tasks
n'_L	number of arcs with length L
m	maximal number of progressive levels
$\overrightarrow{P}$	task path (sequence)
P_i	set of immediate predecessors of task i
r_{ij}	demand of task i for renewable resource type j
$r_{ij}(\tau)$	demand of task i for renewable resource type j at time τ
$s\%$	rate of supplementary tasks
S_i	set of immediate successors of task i
t_i	duration of task a_i
TS_i	total slack of task i
w_i	width of progressive level i, $i = 1, ..., m$

Greek symbols

α_j	availability of renewable resource type j
α_w	total absolute deviation from the average width
η	number of types of nonrenewable resources
ρ	number of types of renewable resources

Calligraphic symbols

$\mathcal{A}$	set of arcs (dependencies)
$\lvert\mathcal{A}\rvert$	number of dependencies in a project structure
$\mathcal{S}$	project structure, set of (to-be-) realized tasks
$\overrightarrow{\mathcal{S}}$	project schedule of project structure $\mathcal{S}$

Chapter 1

Introduction

1.1 Motivation of the thesis

Our society is substantially projectified (Godenhjelm et al., 2015). Around 40% of the global economy is project-based and project management is a fundamental process for producing products and services (Turner, Huemann, et al., 2010). Projects of all types can contribute almost 20% of a country's GDP (Denizer et al., 2013; World Bank, 2012), and have become the standard way of doing business.

To cope with the dynamic business environment and the increased complexity of products and services (Hobday, 2000), 84% of companies run projects simultaneously (Lova et al., 2000) and a similarly high percentage was reported already in the nineties (Payne, 1995). With a slow shift from the long-standing single project management paradigm, the challenges of these multiproject environments are still prevailing.

Several studies have shown that to increase the success of today's projects (Johnson, 2020), where uncertainties are inherent (Hazır and Ulusoy, 2020) and the work is intensified and compressed (Söderlund, 2005), traditional project management approaches are increasingly being replaced by flexible approaches (Ciric, Lalic, et al., 2019; Hidalgo, 2019a; Özkan and Mishra, 2019; Wysocki, 2019) not only in the IT field (Stare, 2014) but also previously unconsidered fields, such as construction (Yasaman et al., 2022) and maintenance projects (Kosztyán, Pribojszki-Németh, et al., 2019). The need to apply new methodologies generated numerous research challenges and the importance of project planning and scheduling has remained unchanged (Serrador, 2013), yet flexible approaches are narrowly studied (Pellerin and Perrier, 2019).

These emerging approaches require flexible project plans, allowing, for example, the possibility of either or both project restructuring and task reprioritization according to the customer's requirements; however, most project planning methods assume a fixed logic plan (Franco-Duran and Garza, 2019) or a limited number of scheduling alternatives (Čapek et al., 2012; Creemers et al., 2015; Hauder et al., 2020; Kellenbrink and Helber, 2015; Servranckx and Vanhoucke, 2019b; Tao and Dong, 2018). There are already a few matrix-based methods available for scheduling structurally flexible projects and multilevel projects (Kosztyán, 2015; Kosztyán and Szalkai, 2020) where certain task realizations and dependency occurrences are considered as variables during the planning phase.

However, there is neither a project database that supports the design, planning, and scheduling of flexible (multi)projects nor a set of complexity and time- or resource-related indicators that are capable of characterizing flexible project plans available. Despite that project data has become a fundamental part of the research, still, a significant amount of existing project databases are often inaccessible, heterogeneous in terms of formats and attributes, and lack standardization. It is thus essential to provide both scholars and practitioners with standardized databases and a set of indicators to allow them to examine flexible projects.

Therefore, the aim of the dissertation was fourfold:

1. To specify a matrix-based method, which can handle
    - [ ] single and multi-level projects,
    - [ ] multiple execution modes,
    - [ ] flexible projects besides traditional ones.
2. To collect existing heterogeneous project databases, including:
    - [ ] simulated (artificial),
    - [ ] real-life projects.
3. To examine the effects of flexibility not only on the project structure but on the project demands as well.
4. To provide a framework for effective planning of flexible (multi)project plans.

1.2 Research questions

Considering the issues and their relevance above, the current study seeks to answer the following research questions:

RQ1: How to create a unified model that can represent the heterogeneous project and multiproject databases available in the literature?

RQ2: How the flexibility of single- and multiproject plans can be modeled?

RQ3: What characterizes the topology (structure) and the different demands of the flexible project and multiproject plans?

RQ4: How is it possible to find feasible (sub)optimal solutions for the single- and multiproject plans considering flexibility?

1.3 Structure of the thesis

The dissertation is organized as follows. After a brief introduction to project management in Chapter 1, the literature is reviewed in Chapter 2 with the related works and databases. In Chapter 3, first, the applied project databases and the considered complexity, time-related, and resource-related indicators are introduced. Then, the flexibility-dependent indicators are specified. In Chapter 4, the applied project databases are compared, and the flexibility effects are examined. Chapter 5 discusses, while Chapter 6 provides validation of the results. A summary is given in Chapter 7, then Chapter 8 considers the limitations of this research and gives directions for future work.

Chapter 2

Literature review

2.1 Projects and their management

2.1.1 Definitions

There are many attempts in the literature to define projects. Most of the authors describe projects as temporary endeavors with specific objectives, uniqueness, complexity, and novelty; constrained by scope, quality specifications, budget, time, and limited resources (see e.g., Gareis, 2000; PMI, 2021; Turner, Huemann, et al., 2010; Wysocki, 2019).

The definition of the project has evolved from unique tasks (Olsen, 1971), which are clearly bounded by the time, cost, and quality parameters. The interpretation later shifted more toward results. With time, the business environment became more dynamic, and also the organizational aspect came into focus. Projects were described by Lundin and Söderholm (1995) as temporary organizations, emphasizing their specific nature (purpose, resources, competencies) and limitation in time compared to the permanent parent organization. Turner, Huemann, et al. (2010) defines the project as *"a temporary organization to which resources are assigned to do work to deliver beneficial change"*.

The temporary organization is *"a unique endeavor in which human, financial and material resources are organized in a novel way to undertake a unique scope of work, of given specification, within constraints of cost and time, so as to achieve beneficial change by quantitative and qualitative objectives"* (Turner, Huemann, et al., 2010).

A strategic viewpoint was also added by Cleland (1994), where projects are considered as building blocks of strategy in response to the changes in the environment.

Di Muro et al. (2021) defines projects as *"functional networks aimed at delivering solutions or business benefits"* (with reference to Sydow et al., 2004; Thiry and Deguire, 2007).

2.1.2 Project lifecycle and typology

The lifecycle of a project typically consists of several consecutive phases. The number and name of these phases often vary, but they are still relatively standard in the literature. According to Schwindt, Zimmermann, et al. (2015), there are five such phases, that also involve managerial tasks, as shown later.

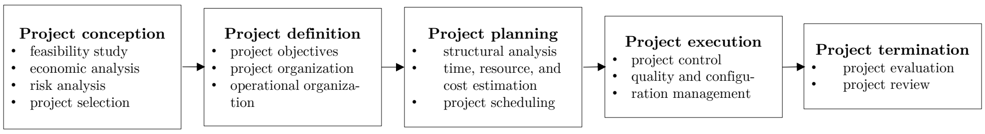


FIGURE 1: Project lifecycle (Schwindt, Zimmermann, et al., 2015)

Starting with *project conception*, the basic idea of the project is analyzed from different perspectives for feasibility. *Project definition* specifies the project objectives and organizational structure. In the *project planning* phase, the activities relations are identified, and their duration, cost, and required resources are estimated for a schedule. During *project execution*, the progress of execution is monitored and, if needed, adjusted for the previously defined plan. Finally, the *project termination* phase evaluates the project's completion and documents it (Schwindt, Zimmermann, et al., 2015). Each of the phases is shown in Figure 1 in detail (see, e.g., Archibald, 2003; Cleland, 2007; Corsten and Corsten, 2000; Görög, 2003; Leybourne, 2007; PMI, 2021).

Projects can be categorized based on many aspects, such as the type of industry, content, size, location, complexity, technology, novelty, environment, customer, etc. One example is given by Turner (2009), where the clarity of goals and methods is used to categorize projects, shown in Figure 2. A similar matrix is proposed by Szűcs (2000). Litke (2007) takes a different approach and defines four groups based on complexity and novelty.

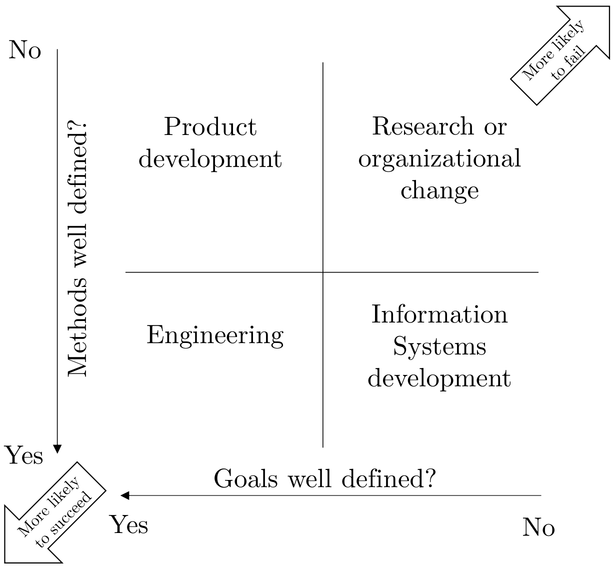


FIGURE 2: Project types based on goals and methods
(based on Turner (2009))

Shenhar, Dvir, et al. (2002) gave an overview of the existing project classification frameworks. Shenhar and Dvir (2007) proposed their diamond model to distinguish between projects and select the right management approach based on the following dimensions: novelty, technology, complexity, and pace, as shown in Appendix A, Figure 39. It is possible to analyze the expected benefits and risks using the framework. The novelty dimension represents the uncertainty of either the project's goal or the market. Different technologies carry different risks and possible benefits. Complexity is related to the organization and the level of formality needed to manage it. Pace affects the planning and urgency of projects. The study of Hansen et al. (2022) found that extending the dimension of pace with impact would further improve the model.

2.1.3 Management of projects

Project management is considered the primary capability of a firm to respond to change and thereby gain competitive leverage (Pellegrinelli et al., 2015; Vuorinen and Martinsuo, 2018).

Westland (2009) defines project management as the *"skills, tools and management processes required to undertake a project successfully."*.

Turner (1993, 2009) explains the three dimensions of project management: the *project* (scope, project organization, stakeholders, quality, cost, time, risk), the *management processes*, followed at each phase of the project lifecycle (plan, organize, implement, control), and the *levels*[1] (integrative, strategic, tactical).

PMI (2021) describe five management process groups employed in a project to meet the objectives. These are: *initiating*, *planning*, *executing*, *monitoring and controlling*, and *closing*.

It is important to note that process groups are not project phases. Process groups interact with each other, usually overlap, can provide inputs and receive outputs from other processes, and can be started and iterated when needed. Figure 3 illustrates the process groups and their typical efforts over time.

In the definition of project management given by Westland (2009), one can notice a vaguely mentioned success criteria. The iron triangle, also referred to as the triple constraint or project triangle, is a fundamental and widely accepted concept (Pollack et al., 2018), an essential criterion to measure project success, i.e., if the project is delivered in time, within budget, and to the agreed level of quality, performance or scope.

The iron triangle has become the standard for assessing project performance. It is typically depicted as a triangle with criteria on the vertices or sides. Change in one criterion, for example, in response to customer demands or resource limitations, can put pressure on other criteria, as they are interconnected. A break in a constraint likely leads to negative consequences (trade-offs) on one or both of the additional

[1] Turner changed the dimension "levels" later to micro- and macro-levels, but the previous classification is intentionally used here.

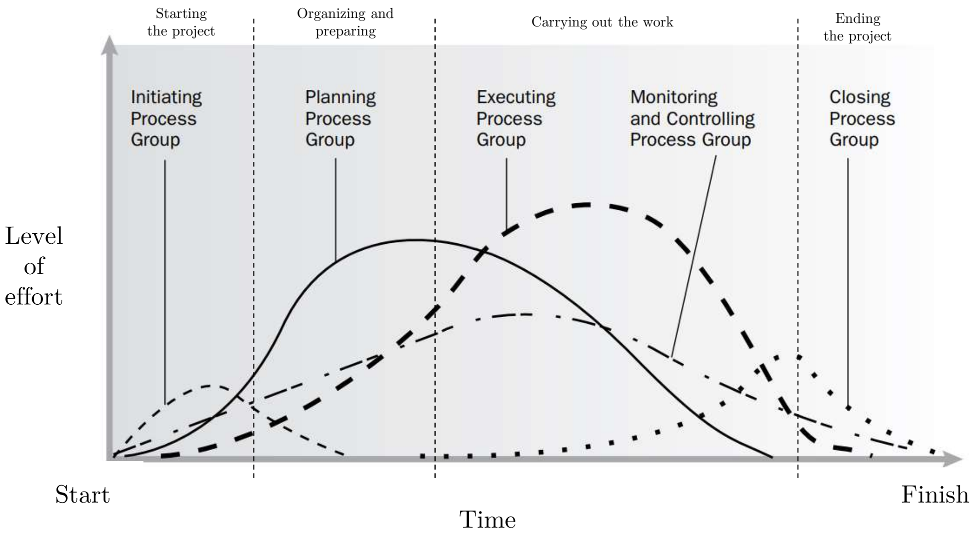


FIGURE 3: Project management process groups and efforts
Based on PMI (2021)

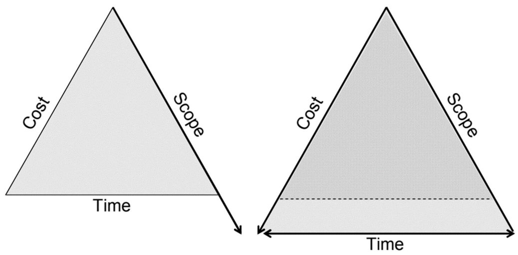


FIGURE 4: Project triangle and a possible scenario
(Van Wyngaard et al., 2012)

two constraint(s) (Van Wyngaard et al., 2012). Figure 4 shows the dynamics when time and cost are affected by the change in scope. The iron triangle is criticized mostly for not having additional criteria for soft aspects, like customer relationship and satisfaction (Pinto, 2013; Pollack et al., 2018; Williams et al., 2015).

Project success is often confused with the success of project management (Papke-Shields et al., 2010), which needs a distinction. Project management success is measured through the project's process and is evaluated at the end (Papke-Shields et al., 2010; Pollack et al., 2018). Project management's success is a subset of project success, a wider concept with many aspects (Radujković and Sjekavica, 2017).

2.1.4 Project management approaches

An important aspect in handling projects is to select the appropriate management approach (Charvat, 2003), as no single best method exists (Špundak, 2014). Project management approaches can also be categorized. A possible grouping is based on goals and solutions (Wysocki, 2019), as shown in Table 1.

The first category has a clear goal and solution and is called traditional project management (TPM). Good examples are construction projects, where requirements are stable, thus no significant changes are expected.

TABLE 1: Project management categories
Based on Wysocki (2019)

		Solution: Clear	Solution: Not clear
Goal	Not clear	Emertxe PM (MPx)	Extreme PM (xPM)
Goal	Clear	Traditional PM (TPM)	Agile PM (APM)

In contrast, agile project management (APM) has clear goals, but it is unclear how to achieve them. Most software development projects fall into this category. Extreme project management (xPM) has vague goals and solutions, that characterize most research and development (R&D) or new product development projects. The fourth category, emertxe (MPx), has no clear goal, but there is already a solution. An example is when the technology exists before it is applied.

2.1.5 Lifecycle of project management

The lifecycle of project management approaches can be differentiated. The traditional approach has a linear or incremental lifecycle where requirements are clearly specified, and changes are not expected during the project.

Agile approaches are developed with recurring changes in mind. They have an iterative or adaptive lifecycle, frequent deliveries to handle uncertainty, and changes in requirements. Similar agile project phases are defined by DeCarlo (2004) and Highsmith (2009). The extreme approach has its dedicated lifecycle, where the main characteristic is that the scope can change after each phase. The different lifecycles defined by Wysocki (2011) for each approach are illustrated in Figure 5.

2.1.6 Traditional and agile project management

Traditional project management brings formal methods of planning and control (Conforto and Amaral, 2016; Kerzner, 2017; Salameh, 2014), however usually faces challenges with increasing levels of uncertainty (Bergmann and Karwowski, 2018; Mattia et al., 2020). Highsmith (2009) defines *agility* as an ability to create and respond to change to create value in a turbulent business environment. Agile approaches are formed from the main principles of the agile manifesto (Fowler, Highsmith, et al., 2001).

Despite being significantly influenced by agile software development methods, APM has already gained popularity in a broader context (Bergmann and Karwowski,

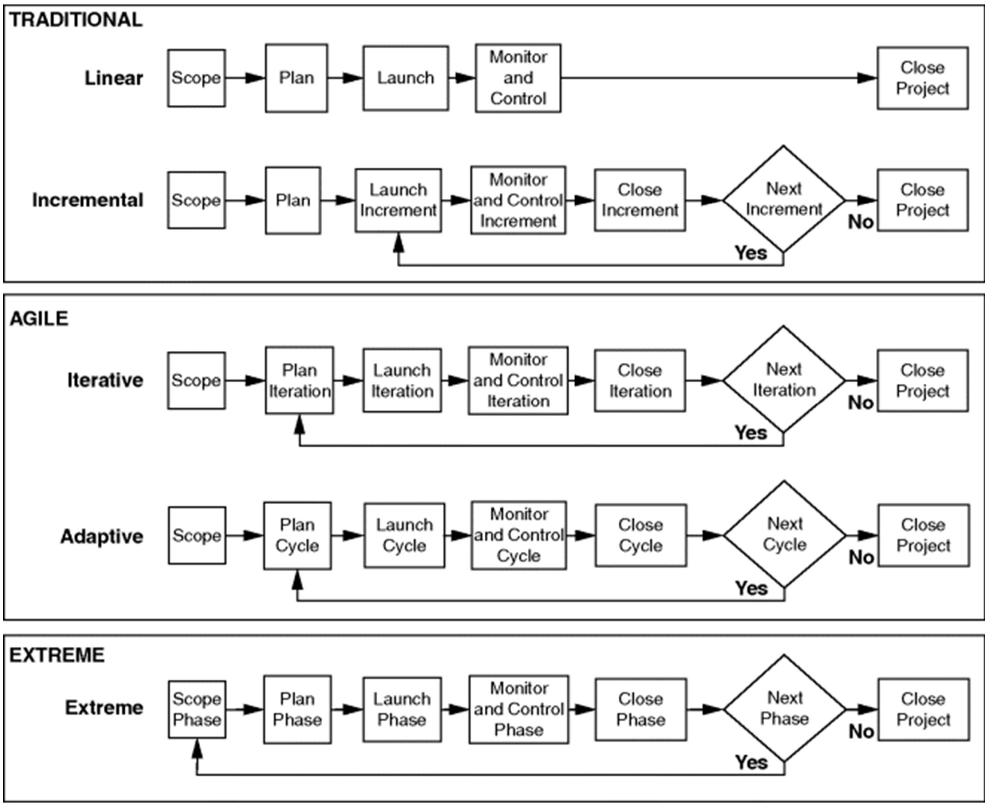


FIGURE 5: Project management lifecycles
Wysocki (2019)

2018; Bianchi et al., 2018; Conforto, Salum, et al., 2014; Owen et al., 2006). TPM tries to predict and minimize change (Ciric, Lalic, et al., 2019), while APM adapts to uncertainty and changes even in later phases of a project. In TPM, phases are rarely revisited, providing no feedback (Bergmann and Karwowski, 2018). APM explores and adapts to customer requirements in short cycles based on feedback, helps to identify errors early (Thesing et al., 2021), and maximizes value (Fowler, Highsmith, et al., 2001).

APM assumes that cost, time (and quality) are fixed, and only the scope can change. APM focuses on prioritized items and requirements that offer the most business value in time. Figure 6 illustrates the difference between traditional and agile project triangles. Unlike TPM, where new features (scope) are added at the expense of cost and delivery date, APM has a relatively small scope, and rapid deliveries at a high rate (Collyer and Warren, 2009), with a greater emphasis on communication over a process or plan (Fowler, Highsmith, et al., 2001). The frequent customer interaction and early concept testing result in a faster time to market and create a positive loop with higher customer satisfaction and economic benefit.

Ciric, Lalic, et al. (2019), identified possible challenges like adapting organizational culture, incompatibility with organizational processes, work prioritization, and alignment among stakeholders. Implementing APM requires a change in the

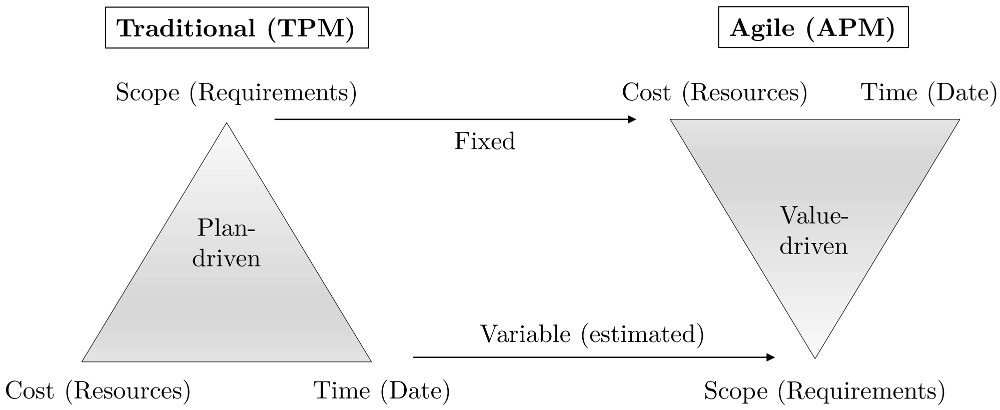


FIGURE 6: TPM and APM project triangles
based on Leffingwell (2010)

organizational culture which is a complicated process and needs support from management (Ciric, Lalic, et al., 2019; Loiro et al., 2019). Dumitriu et al. (2019) mentions larger organizations struggle to adopt agile e.g., due to managing interdependencies between projects and self-organizing teams.

TABLE 2: Comparison of TPM and APM characteristics
Based on Špundak (2014), Dybå and Dingsøyr (2008)

Characteristic	Traditional Project Management (TPM)	Agile Project Management (APM)
Requirements	clear initial requirements; low change rate	creative, innovative; requirements unclear
Clients	not involved	close and frequent collaboration
Documentation	explicit, formal documentation required	tacit knowledge
Project size	bigger projects	smaller projects
Management style	autocratic, prescriptive	affiliate, democratic
Organizational structure	bureaucratic, highly formalised	flexible, cooperative
Organizational support	use existing processes; bigger organizations	prepared to embrace agile approach
Team members	not accentuated; fluctuation expected; distributed team	co-located team; smaller team
System criticality	system failure consequences serious	less critical systems
Project plan	linear	complex; iterative
Quality control	planned in time in details	ongoing control of subresults with client's expectations

The ratio of projects falling into the category of agile is around 70%, according to international research done by Wysocki (2011). Despite the relatively small fraction of traditional projects, project managers continue to apply traditional methods.

Regarding the success of technology projects, Johnson (2020) highlights from the regular CHAOS report that agile projects are three times more likely to succeed[2] [3] than traditional projects, and traditional projects have double the chance to fail[4] and the trend continues. The study also highlights interesting differences regarding project size[5]. Small agile projects succeed three times more than large agile projects; large agile projects succeed twice more than large traditional projects. Small traditional projects succeed six times more than large traditional ones. Agile and traditional only come close to each other in the small project category. The study suggests

[2]Successful project means on time, on budget and satisfied customer
[3]Challenged project means late or over budget, with less than satisfied customer
[4]Failed project means canceled before it is resolved, or resolved and not used
[5]Project size is measured in hours of productive labor:
less than 10,000 considered as small; 30,000-60,000 as medium; 60,000-100,000 as large project

that large projects should be avoided by breaking them down into smaller ones, reducing risk. The detailed success rates are shown in Table 3.

TABLE 3: Project success rates by method and size
Based on Johnson (2020)

Size	Method	Successful	Challenged	Failed
All	Traditional	13%	59%	28%
	Agile	42%	47%	11%
Large	Traditional	8%	56%	36%
	Agile	19%	56%	25%
Medium	Traditional	9%	66%	25%
	Agile	34%	53%	13%
Small	Traditional	45%	46%	9%
	Agile	59%	36%	5%

2.2 Multilevel project management

Management of individual projects is extensively studied in the project management literature (see, e.g., Artto et al., 2008; Atkinson, 1999; Baccarini, 1996; Cooke-Davies, 2002; Kerzner, 2017; Munns and Bjeirmi, 1996; Pinto and Slevin, 1987). Due to today's dynamic business environment, an increasing number of companies are dealing with concurrent projects. Yet, research addressing the multiproject environment, where an organization is executing multiple projects simultaneously, is still scarce. Many authors note that general project management literature is surprisingly biased towards the single project paradigm compared to the multi-project environment (see, e.g., Aritua et al., 2009; Canonico and Söderlund, 2010; Eskerod, 1996; Evaristo and Van Fenema, 1999). As the majority of value resides in multiproject settings (Jerbrant, 2013; Liberatore and Pollack-Johnson, 2003; Maroto et al., 1999; Payne, 1995), further research and focus are necessary for this area (Winter et al., 2006). For organizations relying on projects as their primary means of achieving their strategic objectives, often called project-based organizations, it is not sufficient to manage individual projects efficiently and in isolation; projects need to be in line with the firm's strategy and business goals (Martinsuo and Ahola, 2022). Controlling and organizing these projects and their interdependencies increase the focus on planning also.

In the multiproject context, various, often interchangeably used concepts can be found in the literature. Depending on how an organization's projects are related, one can distinguish programs, and project portfolios (Patanakul and Milosevic, 2009) in the multiproject environment (MPE). Figure 7 shows a possible organizational setting (Patanakul and Milosevic, 2009). Each important concept will be reviewed and clarified in the following paragraphs.

For the multiproject environment, the definition of Fricke and Shenbar (2000) is used: *"Multi-project is understood as a setting in which more than one project is carried*

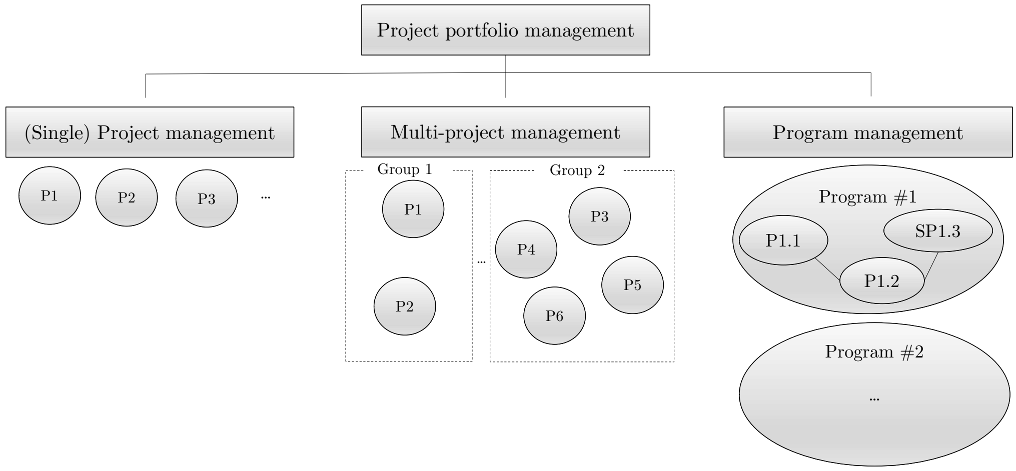


FIGURE 7: Multiproject environment (MPE)
Adapted from Patanakul and Milosevic (2009)

out at the same time. The projects vary in size, importance, required skills and urgency, are in various stages of completion and are using the same pool of resources." The terms "multiproject" and "multiproject environment" might be used interchangeably in the remainder of this dissertation. Blismas et al. (2004) emphasizes the multiplicity of projects in the organization as these projects are not necessarily or directly interrelated (PMI, 2021; Schwindt, Zimmermann, et al., 2015). Turner and Müller (2003) mentions that in this context, projects are managed individually with their own objectives and goals, while the coordination is limited to shared resource allocation (Patanakul, 2012) with emphasis on project management processes, tools, and practices.

Projects in a program are *"[...] mutually dependent, share a common goal, and lead to a single product or service"* (Patanakul and Milosevic, 2009). Turner and Müller (2003) highlights the difference between project and program as the objectives of a program are longer term and less specific. The author makes an important distinction by arguing that strategic objectives of higher order are delivered by managing these projects together. Gareis (2007) further states that programs are not only a collection of projects, and emphasize the strategic nature of programs (as temporary organizations), their larger scope and complexity, and the need for program management to be aligned with the organizational strategy. Besides the common strategic objective, Görög (2011) identified two interdependencies in programs, the common resources used by projects, and the mutual scope dependencies between projects in the program. Müller et al. (2013) stresses the importance and need for project governance.

Rajegopal et al. (2007) defines a project portfolio as *"[...] a group of projects and programs and other work that are bound together to enable the effective management of work and to meet strategic goals of the business."* Turner and Müller (2003) refers to a project portfolio as an organization that is more permanent in nature. The group of projects is managed together to efficiently prioritize resources and thus reduce uncertainty. Authors often consider the management of a portfolio as a dynamic process including continuous reconsideration of active projects, their priorities, and reallocation of resources to balance value (Cooper et al., 1999; Kahn et al., 2013; Meifort, 2016).

From organizational and strategic aspects, two roles are typical. The project client, who initiates projects for their own strategic goals (project-oriented company), and organizations carrying out project activities as external contributors (project-based organizations). Terms are often different (Lundin, Arvidsson, et al., 2015; Sydow et al., 2004) or varied in literature (see, e.g., Gareis, 2007; Görög, 2003; Miterev et al., 2017). Project-based organizations strategically adopt project, program, and project portfolio management as business processes to manage their work and focus on efficiency. Project-oriented companies actively define and manage their portfolio besides their core activities and focus on effectiveness.

In Pennypacker and Dye (2002)'s view, multiproject management is concerned with operational and tactical decisions on capacity allocation and scheduling and is the responsibility of project managers. According to Cooke-Davies (2004) a project portfolio is about "choosing the right project", while project management is about "doing the project right". Project portfolio management involves project selection and prioritization by the executive and senior management, focusing on strategic medium- and long-term decisions. Program management is a special case of multiproject management with a single goal or purpose, while multiproject management generally deals with multiple independent goals (Wysocki, 2019). While projects in a program are interrelated, projects in the portfolio are not necessarily.

Aubry, Hobbs, et al. (2010) notes if projects are compiled into programs and then portfolios, the portfolio can be seen as the overall context and connection to the highest level of the project-based organization. It could also be contended that program management is the primary process for linking strategy to individual projects, limiting project portfolio management to project selection and support areas. Based on the above, it can be concluded that the successful realization of individual projects and programs within a portfolio is important for the success of the portfolio itself and improves the chances of the long-term success of the organization.

The term multi-level project management in this dissertation is understood as the approach to managing multiple projects, programs, and portfolios besides single projects. To perform planning adequately, it is essential to consider projects simultaneously at all planning levels, while recognizing that different levels have different objectives, constraints, and degrees of aggregation. Many approaches do not recognize this and treat multiproject planning problems as a set of independent single project planning problems. Authors have shown already that management of multi-projects is not simply an aggregate of single project efforts and as such requires unique approaches, techniques and tools (De Maio et al., 1994). For instance, optimal resource management is an objective at the tactical level, and the robustness of plans is an objective at all levels. Multi-level management approaches must address these objectives hierarchically.

In organizations managing multiple projects, management faces additional challenges (Elonen and Artto, 2003). They need to carry out projects that run at the same time, share common resources, and have different (often conflicting) goals, complexity and timelines. Such simultaneous handling of projects requires effective identification of the different project and organizational goals and the ability to quickly switch between projects (Patanakul and Milosevic, 2009). Consequently, multiproject managers have to deal with problems that are different from individual projects (Dooley et al., 2005; Pellegrinelli, 1997; Platje et al., 1994), including, for example, a lack of resources, which appears widely in the literature (Cooper et al., 2000, 2001; Zika-Viktorsson et al., 2006).

Balancing limited resources across projects is described as the prime challenge of multiprojects (Dooley et al., 2005; Engwall and Jerbrant, 2003) and has great importance. In a multiproject environment, projects must negotiate priority for resources on an almost daily basis. Jerbrant (2013) mentions challenges due to a lack of slack resources and high levels of uncertainty. The constantly changing work situation requires a flexible and adaptable approach to project portfolio management, which involves a combination of planned and improvisational actions. There is no single best solution to this and the approach must balance both structure and flexibility. Prioritization can take many forms in an organization's project management processes. Organizations' primary goal is often to win increasingly more projects, not necessarily considering the level of available resources. Short-term problem solving is common (Delisle, 2020) that can lead to a vicious circle. The organizations cannot identify the projects that are a priority to implement, thus disrupting the implementation of other projects (Engwall and Jerbrant, 2003; Spuhler and Biagini, 1990) increasingly competing against each other (Dooley et al., 2005; Kuprenas, 2003). Fricke and Shenbar (2000) finds that factors that have low relevance for single projects, such as the assignment of resources, prioritization, and customized management style, play a significant role in the success of multiproject management.

In addition, leaders of organizations often choose short-term and easy to implement or low-budget projects, such as modifying or expanding products. However, this approach will reduce their future success potential and competitive advantage (Cooper et al., 2000, 2001). Elonen and Artto (2003) also drew attention to this bias in decision-making.

It is evident from the diversity of problem areas affecting multiproject management (Elonen and Artto, 2003), that a better understanding and more complex tools are necessary to manage multiple projects effectively. The term multilevel is used in this context to emphasize and express the different scales and their interrelated challenges, which are inherently present when managing multiple projects.

2.3 Project planning and scheduling

Project planning is defined as the establishment of a predetermined course of action for the forecasted environment (Kerzner, 2017). Specifically, it covers the formulation of goals and objectives that explain the work that has to be done, the timeline for the project, and the necessary resources that are required to accomplish the objectives of the project (Zwikael, 2009). Project planning helps to reduce uncertainty, to improve the efficiency of the operation, and to obtain a better understanding of project objectives while providing a basis for monitoring and controlling work (Kerzner, 2017). The planning process (re)defines the objectives and selects the best alternatives to achieve these objectives (PMI, 2021).

Project scheduling is also an integral part of project management as it establishes an allocation of resources over time to perform a set of activities. It is typically concerned with two dependencies; activities that compete for the scarce resources carrying them out, and the precedence constraints between pairs of activities that define the order of execution (Hartmann and Briskorn, 2021).

To identify necessary tasks and to break down the scope of projects hierarchically into smaller, more manageable components, the work breakdown structure (WBS) method is often used during planning and monitoring (PMI, 2021). However, WBS does not include information about the sequence in which the activities should be performed.

Network-based models like the critical path method (CPM), (Kelley Jr, 1961) and project or program evaluation and review technique (PERT), (Malcolm et al., 1959) are used to identify the dependencies between project activities and to create a schedule addressing time also. These early methods solve the project scheduling problem (PSP) without addressing resource constraints. CPM uses a deterministic, fixed time- and cost estimate for the activities, while PERT uses a stochastic approach with three-time estimates (optimistic, most likely, pessimistic) to calculate a weighted average of activity durations considering uncertainty. Although the CPM and PERT approaches are still widely used in practice, they often result in underestimating the overall duration and costs of the project (Klingel, 1966) and are criticized by many, (e.g., Gutierrez and Kouvelis, 1991; Schonberger, 1981). Weaver (1995) argued that these methods are overly rigid and do not allow for changes in project scope.

The traditional network-based project planning tools, such as the CPM (Kelley Jr, 1961), critical chain project management (Goldratt, 1997), metra potential method (Roy, 1962), precedence diagramming method (Wiest, 1981), PERT (Malcolm et al., 1959), eEPC (Van der Aalst, 1999) are no longer able to fully support the strategic decisions of companies (Kosztyán, 2012). These methods cannot handle projects where certain activities must be skipped due to time, cost, or resource constraints. Network-based project planning does not consider that a project can have several possible outcomes and does not provide an opportunity to prioritize activities and subprojects. The characteristics of these methods make it impossible to consider and handle cycles in graphs (Kosztyán and Kiss, 2011). Even the considerably advanced method named graphical evaluation and review technique (GERT) (Pritsker, 1966), which considers decisions and probabilities of possible project scenarios and task durations, ignores the relation between tasks as probability variables (for further stochastic extensions, please refer to Lee, Moeller, et al. (2012)). In addition, network project planning only supports the traditional project management approach and neglects other emerging types, such as agile or hybrid.

2.3.1 Matrix-based project planning

Projects are usually represented as graphs in which activities (i.e., tasks) are depicted either with arcs (activity-on-arrow [AoA] networks) (Demeulemeester, Herroelen, et al., 1996) or nodes (activity-on-node [AoN] networks) (Ren et al., 2021). The matrix representation of projects usually describes an AoN network (Minogue, 2011). Matrix-based project planning can eliminate the shortcomings of traditional methods; it is possible to plan agile and hybrid projects as well as traditional projects. The matrix-based project planning methods are often based on the design (or dependency) structure matrix (DSM) (Kosztyán, 2015; Steward, 1981). The domain mapping matrix (DMM) is an extended version of the DSM, with multiple domains (Danilovic and Browning, 2007). With the numerical DSM (NDSM), the level of dependency relationship between two activities can also be plotted (Chen et al., 2003; Tang et al., 2010). With the stochastic network planning method (SNPM) developed by Kosztyán and Kiss (2010), probabilities or priorities regarding the completion of the activities can be considered. With these methods, various possible network plans can be modeled due to the parallel or sequential completion mode of the tasks. In the case of the project expert matrix (PEM) (Kosztyán, Kiss, et al., 2010), which was created as a further development of the SNPM, the relationships between the activities can be uncertain or stochastic, as can the completion of the activities in the project scenario. The project domain matrix (PDM) proposed by Kosztyán (2015) is used to cope with multiple domains.

Kosztyán (2015) suggested a project domain matrix (PDM), that can be used for both single and multimodal project plans. PDMs allow mandatory and supplementary tasks with priorities and flexible dependencies between tasks. Kosztyán (2020) later extended this matrix-based model to address multiple projects, programs and project portfolios. This matrix-based multiple project management model is denoted M^4.

2.3.2 Resource-constrained (multi)project scheduling problem

The resource-constrained project scheduling problem (RCPSP) is one of the most studied problems in the project planning literature since the 1950s. The classical problem consists of a set of activities that need to be scheduled, subject to precedence and resource constraints to optimize an objective function, e.g., to minimize the overall duration of a project. Several researchers developed both exact and heuristic solutions and various extensions have been investigated. Hartmann and Briskorn (2021) provides an overview and classification of the most important extensions of the RCPSP.

An important extension, the resource-constrained multiproject scheduling problem (RCMPSP), deals with multiple projects using the same resources that must be scheduled without violating the resource constraints. Different variants of the resource-constrained multiproject scheduling problem have also been studied by several researchers since the first introduction of the problem.

Only a minority of the scheduling algorithms address multilevel projects, and they follow the traditional scheduling methodology. In this case, the activities still have a fixed order of execution (Pellerin and Perrier, 2019). Recent algorithms usually decompose multilevel projects into collaborative or competitive single projects, which are solved in a distributed way using agents (Liu et al., 2019; Song et al., 2018). However, these approaches also assume fixed logic plans of projects. For example, software development projects are usually run as a part of a multiproject and are flexible, such as agile, hybrid or extreme project management (Marchenko and Abrahamsson, 2008).

For a survey of the different RCMPSP extensions, see Hartmann and Briskorn (2021), Issa and Tu (2020), and Van Eynde and Vanhoucke (2020). A comprehensive, state-of-the-art survey of the different methods, variants, features, and objectives is also given in (Sánchez et al., 2022).

2.3.3 Flexibility of projects

Projects managed by traditional methods assume that the activities have a fixed order of execution (Pellerin and Perrier, 2019) in the project plans. Software development projects are typically multiprojects, having flexible characteristics like agile, hybrid, or extreme projects (Marchenko and Abrahamsson, 2008), thus the dependencies of tasks are not necessarily fixed (Kosztyán, 2015). The priorities for these tasks are set to select which tasks will be either completed in a short project (a so-called sprint), postponed, or skipped. Agile project management allows such flexible dependencies and priorities of task completion (Kosztyán, 2015; Sajad et al., 2016), while extreme projects allow new and unplanned tasks for common changes in stakeholder requirements. Hybrid approaches allow traditional trade-off methods besides flexibility with multimode task completions (Kosztyán and Szalkai, 2020). Today, flexible approaches are often used in nonsoftware development projects (Hidalgo, 2019a; Papadakis and Tsironis, 2018), such as R&D (Som de Cerff et al., 2018), new product development (NPD) projects (Ciric, Lalic, et al., 2018), construction (Arefazar et al., 2022) and maintenance (Kosztyán, Pribojszki-Németh, et al., 2019).

Broadly defined, flexibility is the magnitude of the room for scheduling decisions (for an overview of the different definitions, see Bernardes and Hanna (2009)).

(Multi) project scheduling is open to several flexibility types; time-related or scheduling flexibility can result from slacks or topological floats (see Tavares (1999) and Vanhoucke, Coelho, Debels, et al. (2008)) in the project plan. This type is the most obvious, and it frequently occurs even in traditional projects. In this case, the precedence relations and the implementation modes remain the same, and only the scheduled start and finish times of the tasks change. Hauder et al. (2020) shows how this flexibility can change the logistical (storing or conveying) task duration, however, it can be implemented by defining the minimal and maximal time lags of an activity-on-node project network (Ren et al., 2021).

The second type is activity (i.e., task) or modal flexibility in which a task can be performed in several modes or the same result can be achieved by carrying out one of the different sets of tasks and utilizing different resource combinations. These alternative (sets of) tasks are modeled by Petri nets in Čapek et al. (2012), by mandatory and optional choices in the project network (Kellenbrink and Helber, 2015), or by the AND/OR network in Tao and Dong (2018). These works extended the resource-constrained (multiple) project scheduling problems (RCPSP or RCMPSP) with alternative activity chains (RCPSP-AC or RCMPSP-AC). Combined with time-related flexibility, Hauder et al. (2020) defined the problem set of the resource-constrained multiple project scheduling problem with alternative activity chains and time-related flexibility (RCMPSP–ACTF).

The third type is dependency flexibility. Some logical dependencies can be omitted if the project task technology does not require a strict sequence. Omitting a dependency lifts the restriction of sequential execution and allows the associated tasks to be performed in parallel or in an arbitrary, relative order.

The fourth type is scope flexibility, in which some low-priority tasks can be omitted or postponed to a later project. This situation reduces the resource demand and can shorten the project duration by sacrificing quality or fulfillment level. The latter two flexibility types appear typically but not exclusively in agile projects (Kosztyán, 2015). Since these flexibilities affect the logical structure of a project, i.e., which tasks are performed and according to which logical dependency they are performed, hereinafter, dependency and scope flexibility are together called structural flexibility.

While structurally flexible projects require flexible project plans, allowing the possibility of project restructuring, task reprioritization or both according to the customer's requirements, most project-planning methods assume a fixed (Franco-Duran and Garza, 2019) logic plan or a limited number of scheduling alternatives (Čapek et al., 2012; Creemers et al., 2015; Hauder et al., 2020; Kellenbrink and Helber, 2015; Servranckx and Vanhoucke, 2019b; Tao and Dong, 2018). In addition, a few matrix-based methods are available for scheduling structurally flexible projects (Kosztyán, 2015; Kosztyán and Szalkai, 2020); among these, some task realizations and dependency occurrences are treated as variables during the planning phase.

2.4 Project related databases and indicators

Project related data

Project databases play a key role in the research of different scheduling and resource allocation methods (Brucker et al., 1999; Hartmann and Briskorn, 2010, 2021) by making them comparable and support the development of new methods (Franco-Duran and Garza, 2019). Three types of data sources can be found in the literature: notional data (e.g., illustrational examples), artificial (generated) data, and empirical (collected) data.

Individual projects are available in various databases, such as Patterson (Patterson, 1976), SMCP and SMFF (Kolisch et al., 1995), PSPLIB (Sprecher and Kolisch, 1996), RG300 and RG30 (Debels and Vanhoucke, 2007; Vanhoucke, Coelho, Debels, et al., 2008), Boctor (Boctor, 1993), MMLIB (Peteghem and Vanhoucke, 2014), the real-life project database by (Batselier and Vanhoucke, 2015), or sets of individual or multiple projects, including MPSPLIB (Homberger, 2007), BY (Browning and Yassine, 2010a), RCMPSPLIB (Vázquez et al., 2015), and MPLIB (Van Eynde and Vanhoucke, 2020).

All these databases contain tasks and dependencies between tasks and renewable resources. However, most databases do not include costs, quality, or nonrenewable resources. Only two datasets consider structural flexibility with alternative subgraphs, the RCPSP-PS dataset (Kellenbrink and Helber, 2015) and ASLIB dataset (Servranckx and Vanhoucke, 2019a). Several databases contain only one completion mode (namely, those of Patterson (Patterson, 1976), SMCP and SMFF (Kolisch et al., 1995), PSPLIB (Sprecher and Kolisch, 1996), RG300 and RG30 (Debels and Vanhoucke, 2007; Vanhoucke, Coelho, Debels, et al., 2008), and the real-life database Batselier and Vanhoucke (2015)), while others contain multiple completion modes (namely, PSPLIB (Sprecher and Kolisch, 1996), Boctor (Boctor, 1993), and MMLIB (Peteghem and Vanhoucke, 2014)).

Some criticism has arisen regarding these simulated project databases. Peteghem and Vanhoucke, 2014 reported four shortcomings of the widely used PSPLIB. One limitation is the low diversity in the complexity of topology networks indicated by the order strength (OS) values. Some of the instances are infeasible. In general, the instances are easy to solve with older procedures. The authors also found that Boctor's dataset contains mainly serial projects, and the renewable resources are hardly restricted by the constraints.

There are further datasets that are worth mentioning, although it is not possible to list all the datasets for the different RCPSP variants. The MT dataset (Vanhoucke, 2010b) is mainly used for schedule risk analysis and earned value management, containing project structures that can be combined with ResSet, have additional resource data and result in the NetRes dataset (Vanhoucke and Coelho, 2018). DC1 (Vanhoucke, Demeulemeester, et al., 2001) and DC2 (Vanhoucke, 2010a) are studied within the context of the RCPSP with discounted cash flows. The CV set (Coelho and Vanhoucke, 2020) contains RCPSP instances that are difficult to solve. MISTA2013 (Wauters et al., 2016) is a dataset and generator for the multi-mode resource-constrained multiple project scheduling problem (MRCMPSP) and combines instances from PSPLIB. The BL (Baptiste and Pape, 2000) and PACK (Carlier and Néron, 2003) datasets are also modifications of the PSPLIB, designed for the context of highly disjunctive and cumulative scheduling of RCPSP, respectively.

Other sources of project data are project generators, such as ProGen (Kolisch et al., 1995), Progen/max (Schwindt, 1995) and Progen/πx (Drexl et al., 2000), RanGen1 and RanGen2 (Demeulemeester, Vanhoucke, et al., 2003; Vanhoucke, Coelho, Debels, et al., 2008), RiskNet (Tavares, 1999), and the multi-network problem generator (MNPG) by Browning and Yassine, 2010a. These project generators have been used to generate several project databases in a controlled manner, such as the PSPLIB (Sprecher and Kolisch, 1996), the RG300 and RG30 (Debels and Vanhoucke, 2007; Vanhoucke, Coelho, Debels, et al., 2008), the MMLIB (Peteghem and Vanhoucke, 2014), and BY (Browning and Yassine, 2010a).

Project related indicators

Project related indicators can be used to classify existing project plans based on different characteristics and as input parameters for the random generation of artificial project plans. The indicators for project plans can be classified into two main groups. The first group characterizes the project structure, including measures of its complexity, and the second group characterizes the project demands, such as resource, time and cost. There are several indicators proposed in the literature. A general overview of indicators and databases is given by Vanhoucke, Coelho, and Batselier (2016). For multiprojects, Browning and Yassine (2010b) gives an overview of the existing indicators, which was extended by Van Eynde and Vanhoucke (2020) recently, showing the relevance and interest for the research of different indicators.

2.5 Synthesis of challenges from literature

In this chapter, the main challenges from the literature are critically reviewed and summarized providing a base for the current research in addition to the already reviewed parts.

To increase the transparency, and reproducibility of the results, important decisions and details of the conducted review process are described. The guidelines of Snyder (2019) and Templier and Paré (2015) were considered, resulting in the following semi-systematic approach with additional manual steps.

To explore the scope of the project related challenges, recent survey articles were collected and reviewed initially. Several databases[6] were identified as the source for journal articles, review papers, proceedings, and books written in English, between

[6]Databases used: ACM, arXiv, CiteSeerX, EconPapers, Emerald, IEEE Xplore, Google Scholar, JSTOR, Microsoft Academic, Semantic Scholar, ScienceDirect, Scopus, SpringerLink, Web of Science, Wiley.

the years 1969 to 2022 (preferably from the last five years). The main keywords[7] were combined into two groups with logical relations and tested for the different sources. Management science and operations research were the two main areas captured. After screening the abstracts (including keywords), the full texts of the obtained manuscripts were analyzed to filter the papers that addressed any relevant challenges until the mapping in Table 4 was finally established for 9 categories. Further examination and filtering based on relevance, journal quality, research methods used, and recency were applied. Some papers were relevant for more than one category, but only the best fit was considered for a better overview. Due to the scarcity of the agile literature, which was even more apparent for agile multiprojects, additional iterations were necessary. By exploring references and citations of existing articles, the previous searches could be extended. Some challenge groups were carefully excluded after consideration, such as certain human (e.g., managing teams and their size) and organizational factors discussed related to agile methods that were out of the scope of the current research.

The literature review showed that many authors are dealing with different sources of uncertainty for projects, Hazır and Ulusoy (2020) gives a classification for the various forms of uncertainty, De Meyer et al. (2002) also investigated uncertainty from different perspectives. They argue that uncertainties are inherent in all projects and can significantly impact project outcomes.

The situation gets more complicated when it comes to multiproject planning, as disturbances to one project influence the others and the situation altogether as a whole becomes less predictable (Zika-Viktorsson et al., 2006). With the high integration of parts, interdependencies (e.g., shared resources) and interactions of projects, the organization also becomes negatively affected, and the need for planning and control increases. Williams (1999) reveals elevated levels of overall complexity and uncertainty in a multiproject environment with an increased number of interdependencies between projects of a program. Gustavsson (2016) suggests limiting the number of interconnected projects and tasks to avoid project overload, a situation in which fragmentation, disturbances and disruptions are highly prevalent (Zika-Viktorsson et al., 2006). Engwall and Jerbrant (2003) identifies challenges with multiple projects as a source of complexity in organizations. They identified issues with long projects which are not broken down into smaller projects, making detailed planning difficult. In addition, changing objectives during projects was also found as a problem. Similarly, Petit and Hobbs (2010) found the change in scope as the most important source of uncertainty at the portfolio level.

Agile projects address uncertainty and reduce project failure (Conboy, 2010; Johnson, 2020), however, according to Dybå and Dingsøyr (2008), because of the higher focus on flexibility and iterative work structures, they also become less predictable.

[7]Keywords used:
Set 1: issue, problem, challenge, limitation, difficulty, obstacle;
Set 2: project, multi-project, multi-level, portfolio, program, management, agile, flexible, planning, scheduling, method, methodology, approach, flexibility

Špundak (2014) suggests that a software development project's scope could change up to 30% during iterations. Hazır and Ulusoy (2020) groups requirement changes into one of the major factors of uncertainty. Due to changing work content, the project network might need to be modified (tasks and relations added or deleted). Zhu et al. (2005) categorizes sources of uncertainties in projects and considers deleted or new activities or precedence relations in projects as network disruptions.

As agile became common for single projects, the focus shifted to the effects of agile projects on multiprojects and portfolios. In this context, the agile characteristics present challenges to the traditional management of multiple projects (Jonas, 2010; Kaufmann et al., 2020; Sweetman and Conboy, 2018) and adjustments such as agility and adaptiveness need to be added (Krebs, 2008; Leffingwell, 2010) to the current state of practice (Stettina and Hörz, 2015) to avoid disjointed, incoherent conflicting agile projects. Unlike single agile projects, agile projects within a multiproject or portfolio context increase difficulties for the management (Rautiainen et al., 2011; Stettina and Hörz, 2015) and introduces a high degree of complexity, with an increased number of interactions due to changing customer needs that also need to be aligned with organizational strategy (Sweetman and Conboy, 2013, 2018). Such dynamic projects need a higher coordination effort and increased adaptiveness to align to the portfolio due to constant change, improvisation and self-organization (Highsmith and Highsmith, 2002; Schwaber and Beedle, 2002; Sweetman and Conboy, 2013). Regarding size and scalability, Uludag et al. (2018) identified 71 challenges for large-scale agile development and Hobbs and Petit (2017) mentions several challenges related to large-scale agile multiprojects. Dumitriu et al. (2019) further categorizes such challenges on project and organizational levels. In general, attempts for agility on the multiproject and portfolio level have been criticized by agile pioneers for being overly complicated (Vähäniitty et al., 2012).

TABLE 4: Summary of challenges from literature for TPM, APM for single and multiple projects
Source: own collection

Challenge cat.	Traditional project	Agile project	Traditional multiproject	Agile multiproject
Uncertainty	Hazır and Ulusoy (2020) and McLain (2009)	Hans et al. (2007) and Laslo and Goldberg (2008)	Gustavsson (2016), Hans et al. (2007), Hazır and Ulusoy (2020), and Laslo and Goldberg (2008)	Dingsøyr and Moe (2014)
Complexity	Danilovic and Sandkull (2002)	Sohi et al. (2016)	Danilovic and Sandkull (2002) and Hans et al. (2007)	Sweetman and Conboy (2018)
Dependencies	Duimering et al. (2006) and Eppinger et al. (1989)	Strode (2016)	Engwall and Jerbrant (2003) and Hans et al. (2007)	Wińska and Dąbrowski (2020)
Priorization	Miranda Mota et al. (2009)	Bakalova et al. (2011), Karlesky and Vander Voord (2008), and Racheva et al. (2008)	Elonen and Artto (2003), Engwall and Jerbrant (2003), and Fricke and Shenbar (2000)	Vähäniitty et al. (2012)
Goals/obj.	Shenhar and Dvir (2007), Van Wyngaard et al. (2012), and Williams (2005)	Serrador and Pinto (2015)	Laslo and Goldberg (2008)	Kaufmann et al. (2020)
Resource alloc.	Turner and Müller (2003)	Dybå, Dingsøyr, and Moe (2014) and Hoda and Murugesan (2016)	Elonen and Artto (2003), Engwall and Jerbrant (2003), Laslo and Goldberg (2008), and Zika-Viktorsson et al. (2006)	Hoda and Murugesan (2016) and Stettina and Smit (2016)
Coordination	Andres and Zmud (2002)	Strode et al. (2011)	Elonen and Artto (2003)	Turek and Werewka (2016)
Adoption	Gareis (1991)	Boehm and Turner (2005)	Aritua et al. (2009) and Elonen and Artto (2003)	Hobbs and Petit (2017) and Marchenko and Abrahamsson (2008)
Location	Aarseth et al. (2014), Evaristo and Scudder (2000), and Evaristo, Scudder, et al. (2004)	Abad et al. (2010), Boehm and Turner (2003), Bose (2008), and Papadopoulos (2015)	Evaristo and Van Fenema (1999)	Lee and Hur (2010)

As shown in Table 4, there are many challenges identified related to projects and their management. It is clear that the uncertainty is amplified with the size and number of projects, and the number of dependencies, especially when multiple projects are interacting with each other and competing for scarce resources leading to their overload. Complexity is ever-increasing due to the number of interconnected elements, and changes in scope and objectives expand the need for coordination. Adopting agile methods alone is a complicated task for an organization, even if agile brings proven benefits, it can also bring some degree of uncertainty in a traditional environment. All things considered, the previously summarized challenges are culminating in two main areas of interest, on the one hand, the literature for flexible projects like agile and hybrid; and on the other hand, the multiproject environment including project portfolios. Surprisingly, their literature is very scarce and definitely needs more focus.

Hall (2016) suggested research opportunities regarding challenges in the choice of project management methodologies (traditional, agile, hybrid), agile scalability, estimation of project completion times, and the availability of project-related data. Vanhoucke (2018) also emphasizes several areas for further research. First, the balance between empirical and artificial project data with an emphasis on a stronger synergy between these two, to increase the realism of experiments. He also identified the area of classification, generation and structuring of project data with the incorporation of flexibility and a better understanding of multiprojects. Van Eynde and Vanhoucke (2020) mentions that literature lags in standardized datasets and the indicators to classify them.

2.6 Research assumptions

By revisiting the research questions formulated in Section 1.2, and critically reviewing the findings and relationships within the literature, it becomes possible to formulate the corresponding research assumptions. The four research assumptions are as follows:

RA1: A model can be created that unifies the different project and multiproject database formats from the literature, including time, cost, renewable-, nonrenewable-resource and quality demands. Existing databases can be imported and further extended with flexible tasks and dependencies into a single, matrix-based database.

RA2: Flexible project plans can be generated from existing traditional (multi)project plans and new possible structures can be added to the model to improve the planning process.

RA3: Existing project-related indicators for topology, time- and resource-related demands can be adapted for flexible projects and multiprojects to analyze the effects of flexibility.

RA4: Flexible multilevel projects can be scheduled and near-optimal solutions can be found considering constraints. A simulation framework can be constructed to handle flexible dependencies and supplementary tasks.

Chapter 3

Methods

3.1 Data sources

The different datasets and libraries mentioned in this dissertation were collected from the project scheduling literature. During the research, suitable data sources were identified that are commonly used and shared by scholars to evaluate scheduling approaches and find the best solutions. The first challenge when dealing with data from literature is usually accessing the different datasets published by various researchers in the field. One of the research's intentions was to review, collect and share the wide range of available data.

The second challenge arises when the data must be handled, as it often has unique formatting and a structure lacking proper documentation. This situation might lead to additional reverse engineering efforts that increase the research time and involve their own risks. Thus, there is a need to harmonize and integrate a wide range of datasets into a library that is accessible, ready to process, and respects the original content.

3.1.1 Data collection and processing

To overcome limitations such as a lack of standardization and database integration efforts, as part of the research, a parser tool was developed (a software program that reads inputs, e.g., a text file for further processing) for the commonly used datasets found in the project scheduling literature. The parser extracts all information from the existing libraries or the output of project generators in an automated and reproducible way. The resulting data are ready for research and analysis and, if needed, can be further adapted to various formats or platforms. Although the parser covers most available formats, the aim is to extend the list of supported extensions continually. The two main dataset categories considered in the current study are *generated* and *empirical*. For an overview of the selected databases, see Table 5.

TABLE 5: Selected project databases and their attributes
Source: own edit

Name	Project Plan	Completion Modes	Projects	Demands	Cited as
Patterson	Generated	Single	Single	Time, renewable resources	Patterson, 1976
PSPLIB	Generated	Single, Multiple	Single	Time, re/nonrenewable resources	Sprecher and Kolisch, 1996
RG30, RG300	Generated	Single	Single	Time, renewable resources	Vanhoucke, Coelho, Debels, et al., 2008
SMCP, SMFF	Generated	Single	Single	Time, renewable resources	Kolisch et al., 1995
Boctor	Generated	Multiple	Single	Time, renewable resources	Boctor, 1993
MMLIB	Generated	Multiple	Single	Time, re/nonrenewable resources	Peteghem and Vanhoucke, 2014
Real-life	Collected	Single	Single	Time, cost, renewable resources	Batselier and Vanhoucke, 2015
MPSPLIB	Generated	Single	Multiple	Time, renewable resources	Homberger, 2007
BY	Generated	Single	Multiple	Time, cost, renewable resources	Browning and Yassine, 2010a
RCMPSPLIB	Generated	Single	Multiple	Time, renewable resources	Vázquez et al., 2015
MPLIB1, MPLIB2	Generated	Single	Multiple	Time, renewable resources	Van Eynde and Vanhoucke, 2020

The parser was written in MATLAB (Mathworks, 2021) and works as follows. After the read-in, preprocessing and verification steps are done according to the defined format of the dataset. Network-related data (tasks and their precedence relations); time-related and resource-related data, including demands and constraints, and if present, data for the costs and multiple modes of completion are collected. Additional fields are captured to retain information from the original data files even if the input is not used directly for scheduling (e.g., the MPM-time field in the case of PSPLIB). The obtained data is processed into a matrix-based representation and saved to a MAT file that contains the data as variables. Continuous, discrete, or no trade-off instance variants are supported by user preference for the different execution modes. The resulting container file can be easily loaded into MATLAB's workspace. Figure 8 gives a schematic overview of how the parser works.

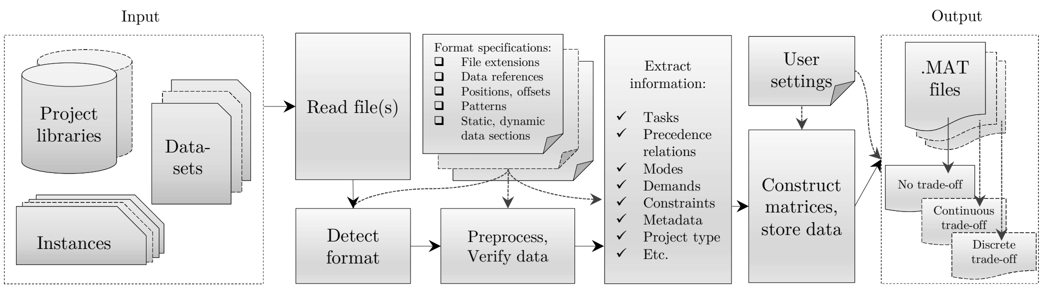


FIGURE 8: The main operation of the parser

The parser addresses renewable resource types, and the tool is designed to be easily extendable for other types (e.g., nonrenewable and doubly constrained resource types). The datasets were selected specifically for the dissertation topic from all parsed libraries and datasets considered. To allow a straightforward comparison of the different indicators, mainly single-mode examples were selected, and cost-related data were not considered, as only one library contains it.

In addition, the source file format is also heterogeneous; therefore, if a scholar wants to test a new method in multiple databases, different parsers must first be written for each project database. An example format is shown in Figure 9 for one of the earliest and simplest project instances by Patterson (1976). However, heterogeneity is not simply a matter of format; tasks might be assigned with different requirements, such as duration, cost, or renewable and nonrenewable resources, furthermore, they can have multiple execution modes.

```
pat1.rcp
14      3
2       1       2
0       0       0       0       3       2       3       4
6       1       0       0       2       9       10
4       0       0       0       3       5       6       7
3       0       0       0       2       8       11
1       0       0       0       1       10
6       1       0       1       1       12
2       1       0       0       2       8       11
1       0       0       0       1       13
4       0       1       1       1       14
3       0       0       1       1       12
2       0       0       1       1       12
3       0       1       0       1       13
5       0       0       0       1       14
0       0       0       0       0
```

FIGURE 9: An example of an early project instance by Patterson (1976)

In Chapter 4, the real project dataset (Protrack) instances are compared to the simulated ones, and the effects are evaluated by introducing flexibility to implementation priority or precedence relations on the project properties.

When generating a new project, only very few structure-related, time-related and resource-related indicators can be set. Therefore, the existing project generators can only generate a few undiscovered and untested project structures. Although developing a new project generator was not a primary aim of this study, considering flexibility extends the domain of the indicator values.

3.1.2 Data selection and construction

A matrix-based model is proposed based on the M^4 model by Kosztyán (2015, 2020), to unify the heterogeneous project databases. The decision was made according to the goal to effectively represent all features of the widely accepted databases, i.e., individual and multiple projects, single- and multimodal completions, renewable and nonrenewable resources.

The proposed matrix-based method is called the *unified matrix-based project-planning model* (UMP), which contains two mandatory, and four supplementary domains (marked with dashed lines), as shown in Figure 10.

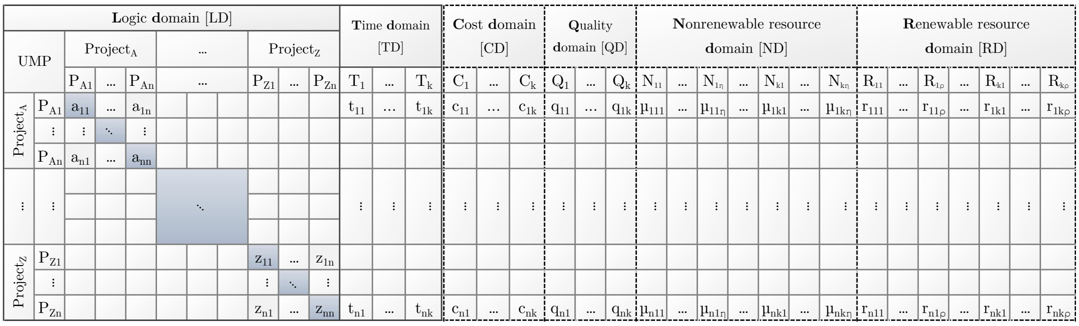


FIGURE 10: Structure of the unified matrix-based project-planning model (UMP)

LD The logic domain is an n by n matrix, where n is the number of tasks. Each cell contains a value from the [0,1] interval.

TD The time domain is an n by k matrix with positive real values, where k is the number of completion modes.

The first mandatory domain is the logic domain, $\mathbf{LD} \in [0,1]^{n\times n}$. The diagonal values in **LD** represent the task priority values. If a diagonal value is 0, the task will not be completed, and if the diagonal value is 1, the task is mandatory. If the diagonal value is between 0 and 1, the task is supplementary, indicating that depending on the decision, it will be either completed or omitted/postponed. In the case of flexible projects, tasks are prioritized by the product owner according to their business value and the risks involved in their development (Abad et al., 2010). To help decision-makers prioritize task completion, several methods, such as MoSCoW rules, are available, and the requirements are prioritized based on their importance by sorting them into the four groups of must-have, should-have, could-have and will-not-have features. In addition to the categories, tasks can be ranked by their importance, or the importance/priority values can be calculated by the analytical hierarchy process (AHP) method (Srivastava et al., 2021). Prioritizing task completions is an essential part of all flexible, such as agile, hybrid, and extreme project management methods. Nevertheless, in this dissertation, only the rate of the existing supplementary (i.e., lower priority) tasks was analyzed; therefore, priority rankings were not studied. Figure 11 shows an example of MoSCoW prioritization of requirements applied by the agile Dynamic System Development Method (DSDM). DSDM method was one of the first to suggest MoSCoW method to prioritize task completion (Stapleton, 1997). This technique indicates that the rate of the mandatory tasks should be approximately 60%. Nevertheless, the concept of task prioritization is generally applied in most agile techniques (Dingsøyr, Nerur, et al., 2012; Govil and Sharma, 2021).

A task can fulfill more than one requirement (see T13); however, usually, to fulfill requirements, more than one task should be completed. In an agile project, only 'MUST (called Maximum Usable SubseT) have' tasks (appr. 60% of tasks and efforts)

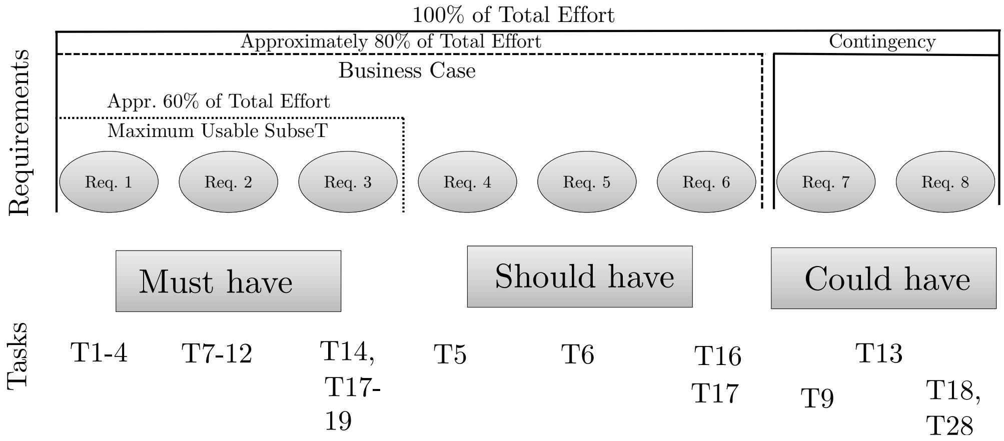


FIGURE 11: An example of MoSCoW of the prioritization of requirements and tasks (based on the guide of DSDM (Stapleton, 1997))

will be completed necessarily; the other tasks (appr. 40%) are supplementary tasks with a different class of priorities.

The out-diagonal values represent the dependencies between the tasks. If an out-diagonal value $a_{ij} = l_{ij} = [\mathbf{LD}]_{ij}$ $(i \neq j)$ is 1, task i precedes task j. In the case of $l_{ij} = 0$, no precedence relation exists from task i to task j. If $0 < l_{ij} < 1$, a flexible dependency exists between task i and task j, indicating that task i may precede or follow task j depending on managers' (algorithm) decisions. All flexible techniques, such as agile, hybrid, or extreme, require flexible dependencies between tasks (Ciriello et al., 2022; Fernandez and Fernandez, 2008).

Since none of the project networks from the considered databases contains any cycles, they can be ordered topologically, and the logic domain of the topologically ordered project networks is an upper triangular matrix (formally, $l_{ij} = 0$ if $i > j$). Although the matrix-based representation does not require acyclic structures, and feedback can be resolved (see, e.g., in Kosztyán, 2015) since most indicators are defined for acyclic project structures, the upper triangular logic domain is considered for the topologically ordered tasks in the rest of this dissertation. Flexible project management allows iterations; however, the databases lack cycles; thus, we can investigate only one iteration at a time. Figure 12 shows how to schedule prioritized tasks using a SCRUMBAN method. SCRUMBAN is a combination of SCRUM, which is the first agile method suggesting iterations called sprints (Hidalgo, 2019b), and the KANBAN, which limits parallel work-in-progress (WIP) tasks (Williams, 2010).

The other mandatory UMP domain is the time-related domain. The positive values of the time domains represent the possible task durations. For each task, k kinds of durations can be assigned; the duration values may also match each other.

Matrix-based methods can also address general precedence relations (GPRs) (Minogue, 2011); however, most databases allow only finish-to-start (F-S) relations between tasks. F-S relations indicate that a successor task can be started only if all predecessor tasks have been finished. It is assumed that tasks can only have F-S relations.

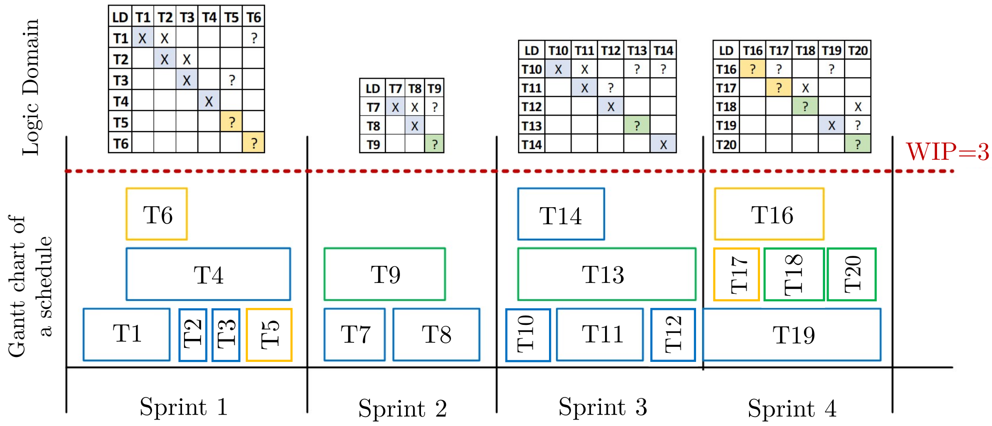


FIGURE 12: Example of a schedule of prioritized tasks with the SCRUMBAN method ('X'=1 represents mandatory (**M**ust have) tasks in diagonal, fixed dependencies in out-diagonal; 0<'?'<1 represents supplementary (either **S**hould have or **C**ould have) tasks in diagonal, or flexible dependencies in out-diagonal).

The additional supplementary domains are as follows:

CD The cost domain, is an n by k nonnegative matrix of the task costs

QD The quality domain, is an n by k, nonnegative matrix of the task quality parameters, where the quality parameters are between [0,1]

ND The nonrenewable resource domain, is an n by $k \cdot \eta$ nonnegative matrix of nonrenewable resource demands, where η is the number of types of nonrenewable resources

RD The renewable resource domain, is an n by $k \cdot \rho$ nonnegative matrix of renewable resource demands, where ρ is the number of types of renewable resources

The optional domains can be either ignored or filled in with zero values. In the current research, **LD**, **TD** and **CD** domains were always used, and if there were renewable resources, the **RD** was also filled in, but if there was no information regarding resources, the **RD** was ignored. The applied database does not contain quality data; therefore, **QD** was omitted. The dissertation focuses only on the structure, time-related and (renewable) resource demands. A nonrenewable domain was not used, as only a minority of the databases have it. Since the real-life database counts of the task and resource costs can also be calculated from the multiplication of resource and time demands, **CD** was not ignored, but like nonrenewable resources, the cost was not in the scope of the analysis.

If the logic domain of the UMP contains either or both supplementary tasks and flexible dependencies, the minimal (maximal) makespan of the project (henceforth, the total project time, TPT) can be specified. When the supplementary tasks and all flexible dependencies are excluded from (included), projects (Kosztyán, 2015) are called *minimal (maximal) project structures*, denoted $\mathcal{S}_{\min}$ ($\mathcal{S}_{\max}$), see the example in Figure 13.

In the case of an early schedule, the maximal (minimal) resource use occurs when all supplementary tasks are included in (excluded from) the project while all flexible dependencies are excluded from (included in) the project structure. These structures are henceforth called *maximin (minimax) project structures* denoted $\mathcal{S}_{\text{maximin}}$ ($\mathcal{S}_{\text{minimax}}$) (see the left side of Figure 13 and Equations (2) through (5)).

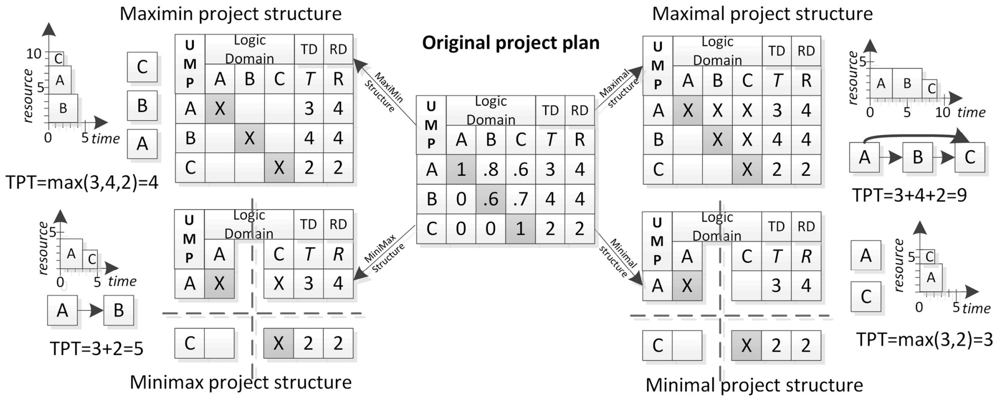


FIGURE 13: Minimal, maximal, minimax and maximin structures of the flexible project plan

To indicate that the minimal, maximal, minimax and maximin structures are the results of a decision, X represents the mandatory tasks and fixed dependencies, while the omitted tasks and independence are represented by empty cells.

3.2 Studied project indicators

Table 6 summarizes the applied indicators on the project plans.

TABLE 6: Applied indicators

Name	Short description	Adapted from	Besides single mode single project, applicable for: single mode multiproject	multi-mode single project	multi-mode multiproject	For results, see
Structural indicators						
I1	number of nodes (i.e., tasks)	Tavares, 1999; Vanhoucke, Coelho, Debels, et al., 2008	X	X	X	F16
I2	serial or parallel structure	Tavares, 1999; Vanhoucke, Coelho, Debels, et al., 2008	X	X	X	F16, F20a, F24
I3	task distribution	Tavares, 1999; Vanhoucke, Coelho, Debels, et al., 2008	X	X	X	F16
I4	rate of short arcs	Tavares, 1999; Vanhoucke, Coelho, Debels, et al., 2008	X	X	X	F16
I5	rate of long arcs	Tavares, 1999; Vanhoucke, Coelho, Debels, et al., 2008	X	X	X	F16
I6	topological float	Tavares, 1999; Vanhoucke, Coelho, Debels, et al., 2008	X	X	X	F16
T-DENSITY	total activity density	Patterson, 1976	X	X	X	F16
XDENSITY	average activity density	Patterson, 1976	X	X	X	F16
C	network complexity	Sprecher, 1994	X	X	X	F16, F20b, F24,F27
CNC	coefficient of network complexity	Davis, 1975	X	X	X	F16
OS	order strength	Mastor, 1970	X	X	X	F16
Time related indicators						
TPT	total project time	Patterson, 1976	X	X	X	F17
XDUR	average activity duration	Patterson, 1976	X	X	X	F17
VA-DUR	variance in activity duration	Patterson, 1976	X	X	X	F17
PCTSLACK	percent of activities possessing positive total slack	Patterson, 1976	X			F17
XSLACK	average total slack per activity	Patterson, 1976	X			F17
TOTSLACK-R	total slack ratio	Patterson, 1976	X			F17, F23, F26, F27
XSLACK-R	average slack ratio	Patterson, 1976	X			F17, F23, F26
PCTFREESLACK	percent of activities possessing positive free slack	Patterson, 1976	X			F17
XFREESLACK	average free slack per activity	Patterson, 1976	X			F17
Renewable resource-related indicators						
RF	resource factor (i.e., density of **RD**)	Kolisch et al., 1995	X			F18
PCTR_j	percent of activities that require resource type j	Patterson, 1976	X			F18
RU	resource use	Demeulemeester, Vanhoucke, et al., 2003	X			F18
DMND_j	the average demand resource type j	Patterson, 1976	X			F18
RC	resource constrainedness	Patterson, 1976	X			F18, F24, F26, F27
RS	resource strength	Kolisch et al., 1995	X			F18
UTIL	utilization of resources	Patterson, 1976	X			F18
TCON_j	constraints of resource j over time	Patterson, 1976	X			F18
OFACT_j	obstruction of resource j	Patterson, 1976	X			F18, F24, F26
UFACT_j	underutilization of resource j	Patterson, 1976	X			F18
NARLF'	resource distribution front/backloaded	Van Eynde and Vanhoucke, 2020	X			F30
Gini	equality distribution of resource demands	Van Eynde and Vanhoucke, 2020	X			F28, F30
Distributional indicators						
$\alpha^{dist}(...)$	variation of multiple indicator values	Labro and Vanhoucke, 2008	X			F28, F30, F30

Table 6 shows that the characterization of both the project structure and demands has several indicators. However, flexibility has no indicators, and quality and cost demands have very few indicators. None of the indicators are interval indicators. This result indicates that the result of each indicator is a scalar or, in the case of multimode completions, a vector. However, in the case of flexible projects, several possible projects have different project demands; therefore, the indicators should be specified as an interval.

Three indicator types are examined. The first group is *structural indicators*, such as complexity and flexibility indicators, which consider only the logic domain of the project domain matrices. The second group of indicators consists of *demand indicators*, which consider other domains, such as time domains (time-related indicators) and renewable resource domains (such as renewable resource-related indicators). The last group is formed by a single indicator, which uses other indicators to show their distributional properties rather than providing any characteristics on its own.

An original logic structure of a project yields an activity-on-node network, which is denoted as $G = (N, \mathcal{A})$ directed graph, where $N = \{A_1, ..., A_n\}$ (A_i is often shortened to i) is the set of nodes (i.e., tasks), and $\mathcal{A} \subset N \times N$ is the set of arcs (i.e., dependencies). $n = |N|$ is the number of tasks, and $|\mathcal{A}|$ is the number of dependencies. Furthermore, the matrix representation of the logic plan is the logic domain (LD) of the UMP matrix, where $\mathbf{LD} \in \{0,1\}^{n\times n}$, for each $i \leq n$ $[\mathbf{LD}]_{ii} = 1$, and for each $i \neq j$, we have $\left(A_i, A_j\right) \in \mathcal{A}$ if and only if $[\mathbf{LD}]_{i,j} = 1$ (otherwise $[\mathbf{LD}]_{i,j} = 0$).

Since none of the project databases considers flexible project structures, flexible project structures are generated in the first step. Let $\mathbf{LD} \in \{0,1\}^{n\times n}$ and $\mathbf{LD}' \in [0,1]^{n\times n}$ the modified logic domain as follows:

$$l'_{ij} = [\mathbf{LD}']_{ij} := \begin{cases} u_{ij} \text{ if } l_{ij} = 1 \text{ and } v_{ij} \leq fp \\ l_{ij} \text{ otherwise} \end{cases} \tag{1}$$

where $l_{ij} = [\mathbf{LD}]_{ij}$, $u_{ij}, v_{ij} \sim U[0,1]$ are uniformly distributed random probability variables (r.v.), and $fp \in [0,1]$ is a fixed flexibility parameter set for computer runs. The goal is to have the ratio of the number of (supplementary tasks + flexible dependencies) w.r.t. the total number of LD elements is approximately fp, which is ensured by "$v_{ij} \leq fp$". The *weights* of these flexible objects are set by the r.v. u_{ij}. Note that $\mathbf{LD}'$ already contains flexible dependencies ($i \neq j$) and supplementary tasks ($i = j$). However, complexity and time-related and resource-related indicators address only fixed project structures.

The modified logic domain is used to specify only the minimal, maximal, minimax and maximin structures, as follows:

$$l_{ij}^{\text{min}} = \left\lfloor l'_{ij} \right\rfloor, \tag{2}$$

$$l_{ij}^{\text{max}} = \left\lceil l'_{ij} \right\rceil, \tag{3}$$

$$l_{ij}^{\text{minimax}} = \begin{cases} \left\lfloor l'_{ij} \right\rfloor & \text{if } i = j \\ \left\lceil l'_{ij} \right\rceil & \text{if } i \neq j \text{ and } \lfloor l'_{ii} \rfloor = \left\lfloor l'_{jj} \right\rfloor = 1 \\ 0 \text{ otherwise} \end{cases}, \tag{4}$$

$$l_{ij}^{\text{maximin}} = \begin{cases} \left\lceil l'_{ij} \right\rceil & \text{if } i = j \\ \left\lfloor l'_{ij} \right\rfloor & \text{if } i \neq j \end{cases}, \tag{5}$$

where $l_{ij}^{\text{min}}, l_{ij}^{\text{max}}, l_{ij}^{\text{minimax}}, l_{ij}^{\text{maximin}}$ are the (i,j) cells of the logic domains of the minimal, maximal, minimax and maximin structures, respectively, with $i, j = 1, 2, .., n$ (see Figure 13). [1]

Minimal, maximal, minimax and maximin structures are also included in the databases. Of course, any other possible implementation structure can be specified by rounding up or down the cell values of the logic domain. However, in the case of single completion modes and the early schedule, the minimal structure provides the minimal task duration and minimal project budget, while a maximal structure provides the highest project score (widest project scope). In addition, the minimax (maximin) structure provides the highest (lowest) renewable resource demands.

For comparability reasons, the real and artificial databases can be examined only for single projects. Individual and multiple projects can be compared by calculating the average indicators per project. However, the calculation of most indicators differs in the single and multimode cases. To avoid the confusion and additional efforts of implementing and using different definitions for the same indicator, each project instance can be analyzed with fixed modes. For multimode databases, this means that the number of generated instances will be multiplied by the number of modes.

3.2.1 Structural indicators

Two structural indicator types are investigated in detail. The first group describes the rates of the flexible dependencies and supplementary tasks, and the second group describes the project structure complexity.

Structural flexibility. First, set

$$S\text{-SET} := \{l'_{ii} | l'_{ii} \sim P(0,1)\} \tag{6}$$

$$F\text{-SET} := \{l'_{ij} | l'_{ij} \sim P(0,1), i \neq j\} \tag{7}$$

where $P(0,1)$ is an arbitrary continuous distribution on interval]0,1[. Then, let

[1] The $\lceil \cdot \rceil$ ($\lfloor \cdot \rfloor$) operators denote the rounding up (rounding down) of real numbers.

fp = *flexibility parameter*, shows the total number of flexible dependencies and supplementary tasks across all tasks and dependencies as follows:

$$fp = \frac{|F\text{-SET} \cup S\text{-SET}|}{n(n+1)/2} \tag{8}$$

(The fp is set before the computer runs as the *approximate* ratio of flexible objects in Equation (1), while Equation (8) calculates the *exact* value of this ratio. Hereafter, we use this latter value of fp.)

$f\%$ = *rate of flexible dependencies* shows the sum of flexible dependencies across all dependencies as follows:

$$f\% = \frac{|F\text{-SET}|}{n(n-1)/2} \tag{9}$$

$s\%$ = *rate of supplementary tasks* shows the sum of supplementary (prioritized) tasks across all tasks as follows:

$$s\% = \frac{|S\text{-SET}|}{n} \tag{10}$$

Observe that $fp = \frac{a+b}{c+d}$ if $f\% = \frac{a}{c}$ and $s\% = \frac{b}{d}$, which has the notation $\frac{a}{c} \boxplus \frac{b}{d} = \frac{a+b}{c+d}$. For a, b, c, d positive (in this case) $\frac{a}{c} \boxplus \frac{b}{d}$ is always between $\frac{a}{c}$ and $\frac{b}{d}$, thus fp is always between $f\%$ and $s\%$, and all three depend only on Equation (1).

Figure 14 shows the mechanism of generating flexibility. The left side of the Figure 14 shows the original logic domain, where the flexibility parameter is set to be 0.4. In the first step, fixed dependencies/mandatory tasks (denoted by the "X" symbol) become flexible (denoted by "?", where "?" indicates a number between 0 to 1). The right side of Figure 14 shows the minimal structure of the project. The center of Figure 14 shows three possible outcomes from $\binom{10}{4}$. Because the number of "X" symbols is 10, we have $fp = 0.4$.

Outcome i retains all tasks, but cuts almost all dependencies, while outcome j retains only one task from the original project. In the general case, several dependencies are cut, and several tasks are omitted, e.g., in outcome k.

The following sections give exact mathematical definitions of the indicators listed in Table 6. Using these indicators, the databases can be compared and it supports the decision of researchers to find the closest databases for their case or problem to study.

Structural complexity. Denote $\mathcal{S}$ a realized project structure, $\mathbf{LD} \in \{0,1\}^{n \times n}$ of $\mathcal{S}$, $|\mathcal{A}| = \sum_{i \neq j} l_{ij}$ ($l_{ij} = [\mathbf{LD}]_{ij}$) is the total number of dependencies (arcs) between tasks.

I_1, the number of tasks (nodes), is calculated as follows:

$$I_1 := n \tag{11}$$

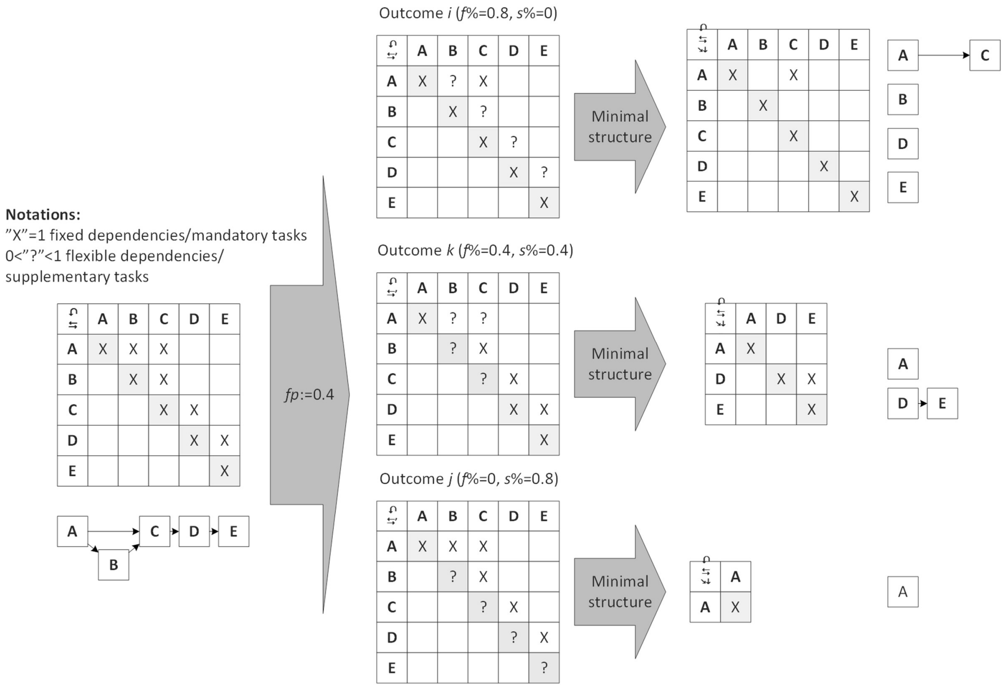


FIGURE 14: Example of generating flexibility

I_2, the serial-parallel structure, measures the closeness to a serial or parallel completion. For I_2, the following notations are needed: S_i (P_i) denotes the *set* of immediate successors (predecessors) of task i. For topologically ordered, acyclic project networks, $|S_i| = \sum_{j=i+1}^{n} l_{ij}$, $|P_i| = \sum_{j=1}^{i-1} l_{ji}$. The progressive ($PL_i$) and regressive ($RL_i$) level *numbers* of each task i can be calculated as follows:

$$PL_i := \begin{cases} 1 & \text{if } P_i = \emptyset \\ \max_{j \in P_i} PL_j + 1 & \text{if } P_i \neq \emptyset \end{cases} \tag{12}$$

and

$$RL_i := \begin{cases} m & \text{if } S_i = \emptyset \\ \min_{j \in S_i} RL_j - 1 & \text{if } S_i \neq \emptyset \end{cases} \tag{13}$$

where $m = \max_i PL_i$. Next, have the following:

$$I_2 := \begin{cases} 1 & \text{if } n = 1 \\ \frac{m-1}{n-1} & \text{if } n > 1 \end{cases} \tag{14}$$

I_3, the task distribution, measures the distribution of tasks over the progressive levels by calculating the total absolute deviations.

First, define the jth progressive *level* of $j = 1, ..., m$ as follows: $\mathbf{PL}_j := \{i \leq n : PL_i = j\}$, i.e., the *set* of all tasks having progressive level number j. Then,

$$I_3 := \begin{cases} 0 & \text{if } m = 1 \text{ or } m = n \\ \frac{\alpha_w}{\alpha_{\max}} = \frac{\sum\limits_{j=1}^{m} |w_j - \overline{w}|}{2(m-1)(\overline{w}-1)} & \text{if } 1 < m < n \end{cases} \tag{15}$$

where $w_j = |\mathbf{PL}_j|$ is the width (size) of progressive level $j = 1, ..., m$, $w = (w_1, w_2, ..., w_m)$ is the vector containing the widths of each progressive level, and $\overline{w} = n/m$, α_w is the total absolute deviation from the average width. Then, $\alpha_{\max}$ is the maximal value of α_w of a network (ranging for all possible $\mathcal{A}$); thus, [2] $\alpha_{\max} = (m-1)(\overline{w}-1) + (n - m + 1 - \overline{w}) = 2(m-1)(\overline{w}-1)$.

I_4, the ratio of *short* arcs. The length of an "arc" (called a path in graph theory) between tasks i_1 and i_2 is defined as $L(i_1, i_2) := |PL_{i_1} - PL_{i_2}|$, the difference between their progressive level numbers. Arcs of length 1 are called *short*, and $D := \sum\limits_{j=1}^{m-1} w_j \cdot w_{j+1}$ is the *maximal* number of short arcs. n'_L denotes the number of arcs of length L for $1 \leq L \leq m-1$. Then, I_4 is calculated as follows:

$$I_4 := \begin{cases} 1 & \text{if } D = n - w_1 \\ \frac{n'_1 - n + w_1}{D - n + w_1} & \text{if } D > n - w_1 \end{cases} \tag{16}$$

I_5, the ratio of *long* arcs ($L > 1$), is calculated as follows:

$$I_5 := \begin{cases} 1 & \text{if } |\mathcal{A}| = n - w_1 \\ \frac{\left(\sum\limits_{L=2}^{m-1} n'_L \frac{m-L-1}{m-2}\right) + n'_1 - n + w_1}{|\mathcal{A}| - n + w_1} & \text{if } |\mathcal{A}| > n - w_1 \end{cases} \tag{17}$$

I_6, the topological float, considers the differences between the regressive and progressive level numbers of task i, i.e., $|RL_i - PL_i|$, as follows:

$$I_6 := \begin{cases} 0 & \text{if } m \in \{1, n\} \\ \frac{\sum\limits_{i=1}^{n} |RL_i - PL_i|}{(m-1)(n-m)} & \text{if } m \notin \{1, n\} \end{cases} \tag{18}$$

CNC, the coefficient of network complexity, is calculated as follows:

$$\text{CNC} = \frac{|\mathcal{A}|}{n} \tag{19}$$

OS, the order strength, is calculated as follows:

$$\text{OS} = \frac{|\mathcal{A}|}{n(n-1)/2} \tag{20}$$

[2]The maximal value of α_w is achieved (n and m are fixed, $\sum_{j=1}^{m} w_j = n$) when all levels are singletons, except for one with $n - (m-1)$ tasks; repetitive use of the inequality $|a - \overline{w}| + |b - \overline{w}| < |a - 1 - \overline{w}| + |b + 1 - \overline{w}|$ for $1 < a \leq \overline{w} \leq b < n$ proves this extrema.

C, the network complexity, is calculated as follows:

$$C = \begin{cases} \frac{\log \frac{|\mathcal{A}|}{n-1}}{\log \frac{n^2-1}{4(n-1)}} & \text{if } n \text{ is odd} \\ \\ \frac{\log \frac{|\mathcal{A}|}{n-1}}{\log \frac{n^2}{4(n-1)}} & \text{if } n \text{ is even} \end{cases} \tag{21}$$

T-DENSITY, the total activity density, is calculated as follows:

$$\text{T-DENSITY} := \sum_{i:=1}^{n} \max\{0, |P_i| - |S_i|\} \tag{22}$$

(S_i and P_i were defined immediately before I_2.)

XDENSITY, the average activity density, is calculated as follows:

$$\text{XDENSITY} := \frac{\text{T-DENSITY}}{n} \tag{23}$$

Flexibility-related structural indicators. All structural indicators depend on the realized structure ($\mathcal{S}$), i.e., on the set of the included flexible dependencies and supplementary tasks from $\mathbf{LD}' \in [0,1]^{n \times n}$. I_1 = number of tasks; therefore, $I_1(\mathcal{S}_{\min}) = I_1(\mathcal{S}_{\text{minimax}}) \leq I_1(\mathcal{S}) \leq I_1(\mathcal{S}_{\max}) = I_1(\mathcal{S}_{\text{maximin}})$. Nevertheless, since the fixed dependencies between the supplementary tasks must be excluded if the supplementary tasks are excluded, the minimal (maximal) structures are the lower (upper) bounds of C. The CNC and OS indicators of these cases are those in which only mandatory tasks exist. Regarding the other structural indicators, the connection between them and the maximal-minimal structures is not obvious, and no such rules can be defined.

3.2.2 Time-related indicators

To ensure the validity of the comparison of the simulated and real-life datasets, only networks with single modes are considered. With an additional setup, multiple modes are also explored separately, however without a possible direct comparison to the real-life databases. Denote $\mathcal{S}$ a realized project structure that decides the non-mandatory tasks and dependencies *from* $\mathbf{LD}' \in [0,1]^{n \times n}$. In the following, all quantities depend on $\mathcal{S}$, but indicating $\mathcal{S}$ is omitted everywhere. For example, $\mathcal{S}$ determines $\mathbf{LD}'' \in \{0,1\}^{n'' \times n''}$ from $\mathbf{LD}' \in [0,1]^{n \times n}$, However, simply denote $\mathbf{LD}''$ and n'' by $\mathbf{LD}$ and n, similarly for $\mathbf{TD}$, and $|\mathcal{A}| = \sum_{i<j} l_{ij}$ ($l_{ij} = [\mathbf{LD}]_{ij}$). Denote $t_i := [\mathbf{TD}]_{ii}$ as the duration of task i and $\overrightarrow{P}$ = "$a_1 \prec a_2 \prec \ldots \prec a_N$" a path of preceding tasks, where $a_j \prec a_{j+1}$ indicates $l_{a_j,a_{j+1}} = 1$ for $1 \leq j < N$ ($N \leq n$). $\ell(\overrightarrow{P}) := N$ is the *length* of the path, and $d(\overrightarrow{P}) := \sum_{i \in \overrightarrow{P}} t_i$ is the *duration* of path $\overrightarrow{P}$. A path $\overrightarrow{L}$ is called the *longest* or *critical* path if $d(\overrightarrow{L})$ is maximal among all paths. Next, the TPT, the total project time, is calculated as follows:

$$\text{TPT} := d(\overrightarrow{L}) \tag{24}$$

for any longest path $\overrightarrow{L}$. $\overline{\text{X}}$DUR, the average task duration, is calculated as follows:

$$\overline{\text{X}}\text{DUR} := \frac{1}{n}\sum_{i=1}^{n} t_i \tag{25}$$

VA-DUR, the variance in task duration, is calculated as follows:

$$\text{VA-DUR} := \frac{1}{n-1}\sum_{i=1}^{n}\left(t_i - \overline{\text{X}}\text{DUR}\right)^2 \tag{26}$$

PCTSLACK, the percent of tasks with positive total slack, is calculated as follows:

$$\text{PCTSLACK} := \frac{1}{n}\sum_{i=1}^{n}\begin{cases}1 & \text{if } LS_i - ES_i > 0\\ 0 & \text{if } LS_i - ES_i = 0\end{cases} \tag{27}$$

where LS_i (ES_i) is the latest (earliest) start time, and $TS_i := LS_i - ES_i$ is the total slack of task i.

XSLACK, the average total slack per task, is calculated as follows:

$$\text{XSLACK} := \frac{1}{n}\sum_{i=1}^{n} TS_i \tag{28}$$

TOTSLACK-R, the total slack ratio, is calculated as follows:

$$\text{TOTSLACK-R} := \frac{\sum_{i=1}^{n} TS_i}{TPT} \tag{29}$$

XSLACK-R, the average slack ratio, is calculated as follows:

$$\text{XSLACK-R} := \frac{XSLACK}{TPT} \tag{30}$$

PCTFREESLK is the percent of tasks with positive free slack. First, the earliest finishing time of task j is $EF_j = ES_j + t_j$; then, denote $FS_i := \min_{l_{ij}=1} ES_j - EF_i$ the free slack of task i (lowest early start of successors - early finish). Here, have the following:

$$\text{PCTFREESLK} := \frac{1}{n}\sum_{i=1}^{n}\begin{cases}1 & \text{if } FS_i > 0\\ 0 & \text{if } FS_i = 0\end{cases} \tag{31}$$

XFREESLK, the average free slack per task, is calculated as follows:

$$\text{XFREESLK} := \frac{1}{n}\sum_{i=1}^{n} FS_i \tag{32}$$

Flexibility impacts of the time-related indicators. Since the average task duration and variance in activity duration depend on the inclusion/exclusion of tasks but not on their dependencies (see Equations (26) and (25)), the following equations are easy to verify:

$$\overline{\text{X}}\text{DUR}(\mathcal{S}_{\text{max}}) = \overline{\text{X}}\text{DUR}(\mathcal{S}_{\text{maximin}}) \tag{33}$$

$$\overline{\text{X}}\text{DUR}(\mathcal{S}_{\text{min}}) = \overline{\text{X}}\text{DUR}(\mathcal{S}_{\text{minimax}}) \tag{34}$$

$$\text{VA-DUR}(\mathcal{S}_{\text{max}}) = \text{VA-DUR}(\mathcal{S}_{\text{maximin}}) \tag{35}$$

$$\text{VA-DUR}(\mathcal{S}_{\text{min}}) = \text{VA-DUR}(\mathcal{S}_{\text{minimax}}) \tag{36}$$

Large samples. Large samples refer to large n for which the central limit theorem (CLT) can be used. Here, some mathematical results regarding $\overline{\text{X}}\text{DUR}(\mathcal{S})$ are offered. Similar results are also used for resource indicators, such as RF, PCTR, RU, DMND, and RC in Equation (48).

$\overline{X}DUR(\mathcal{S})$ contains (finally) mandatory tasks only; thus, consider $\mathcal{S} \subseteq \mathbb{I}_n$, where denote $\mathbb{I}_n := \{1, 2, ..., n\}$, and let $s = |\mathcal{S}|$.

In the following, it is assumed that n and s are large numbers, $t_i \sim U(a, b)$ (for $i \in \mathbb{I}_n$) are uniform random variables (**r.v.**) on the *fixed* finite interval $[a, b] \subset \mathbb{R}$, and t_i are independent and identically distributed (**i.i.d.**) r.v.

STEP ONE: n and $\mathcal{S}$ are fixed. Next, $\overline{X}DUR(\mathcal{S})$ is the mean of s i.i.d. uniform r.v., and thus, the CLT yields the following:

$$\frac{\overline{X}DUR(\mathcal{S}) - \mu}{\frac{\sigma}{\sqrt{s}}} \sim \Phi(0, 1) \tag{37}$$

where:

$$\mu = E\left(\overline{X}DUR(\mathcal{S})\right) = \frac{a+b}{2} \quad , \quad \sigma = D(\overline{X}DUR(\mathcal{S})) = \frac{|b-a|}{\sqrt{12}} \tag{38}$$

and $\Phi(0, 1)$ is the standard normal distribution[3]

STEP TWO: n is fixed, but $\mathcal{S}$ may be any nonempty subset of $\mathbb{I}_n$, i.e., the event space is currently the power set of $\mathbb{I}_n$: $\Omega = \mathcal{P}(\mathbb{I}_n)$. Next, consider $\overline{X}DUR(\mathcal{S})$ on Ω and use the notation $\overline{\mathcal{X}}_{DUR}$ instead of $\overline{X}DUR(\mathcal{S})$. The probability of *any* $\mathcal{S}$ is $\frac{1}{n!}$, $E(\overline{\mathcal{X}}_{DUR}[\mathcal{S}]) = \mu$ and $D\left(\overline{\mathcal{X}}_{DUR}[\mathcal{S}]\right) = \frac{\sigma}{\sqrt{s}}$ when $s = |\mathcal{S}|$, which has the probability $\binom{n}{s}/2^n$; thus, having the following:

[3] In the denominator of Equation (37), one may write $\sqrt{\text{VA-DUR}(\mathcal{S})}$ instead of $\frac{\sigma}{\sqrt{s}}$.

$$D\left(\overline{\mathcal{X}}_{DUR}\right) = \sqrt{\frac{1}{2^n}\sum_{s=1}^{n}\binom{n}{s}\left(\frac{\sigma}{\sqrt{s}}\right)^2} = \sigma\sqrt{\frac{1}{2^n}\sum_{s=1}^{n}\frac{\binom{n}{s}}{s}} \tag{39}$$

Finally, the following is obtained by the CLT:

$$\frac{\overline{X}DUR(\mathcal{S}) - \mu}{D\left(\overline{\mathcal{X}}_{DUR}\right)} \sim \Phi\left(0, 1\right) \tag{40}$$

In the case $|\mathcal{S}|$ is limited, i.e., $c \leq |\mathcal{S}| \leq d$ is required for some fixed $c \leq d \leq n$, Equation (39) becomes the following:

$$D\left(\overline{\mathcal{X}}_{DUR}\right) = \sigma\sqrt{\frac{1}{2^n}\sum_{s=c}^{d}\frac{\binom{n}{s}}{s}} \tag{41}$$

3.2.3 Resource-related indicators

Denote $\mathcal{S}$ a realized project structure and $\mathbf{LD} \in \{0,1\}^{n\times n}$, $\mathbf{T} \in \mathbb{R}^n_+$ and $\mathbf{RD} \in \mathbb{R}^{n\times\rho}_+$ domains of the matrix representation of $\mathcal{S}$, where n is the number of tasks and $|\mathcal{A}| = \sum_{ij,i\neq j} l_{ij}$ ($l_{ij} = [\mathbf{LD}]_{ij}$). Denote $t_i = [\mathbf{TD}]_{ii}$ the duration of task i and TPT the duration of the project, and $r_{ij} = [\mathbf{RD}]_{ij}$ the resource demand of task i of resource j.

$\overrightarrow{\mathcal{S}}$ is a project *schedule* of project structure $\mathcal{S}$ if for each realized task $a_i \in \mathcal{S}$, the interval $T_i \subseteq [0, \mathrm{TPT}]$ is determined when a_i is addressed (scheduled). To ensure compatibility with other papers, the redundant notation $a_i(T) \in \overrightarrow{\mathcal{S}}$ is used.

Denote $S(a_i(T)) \in [0, TPT - t_i]$ the start and $F(a_i(T)) \in [t_i, TPT]$ the finish time of task i. The early schedule, denoted $\overrightarrow{\mathcal{S}}_{\min}$, satisfies $\forall a_i(T) \in \overrightarrow{\mathcal{S}}_{\min}\ S(a_i(T)) = \mathrm{ES}_i$ and $F(a_i(T)) = \mathrm{EF}_i$. Denote the *resource demand* j of task i at time τ as follows:

$$r_{ij}(\tau) := \begin{cases} r_{ij} \text{ if } a_i(T) \in \overrightarrow{\mathcal{S}}, \tau \in T_i \\ 0 \text{ otherwise} \end{cases} \tag{42}$$

Furthermore, denote the total (renewable) resource *demand* of j at time τ as $r_j(\tau) = \sum_i r_{ij}(\tau)$, where $\tau \in [0, \mathrm{TPT}]$.

Nonscheduled. RF, the resource factor, is the density of **RD**, the resource matrix from a domain mapping matrix (DMM). RF gives the rate of how often resources required are from all possible resource type-activity pairings. Higher RF values indicate a more complex scheduling problem.

$$\mathrm{RF} := \frac{1}{n\rho}\sum_{i=1}^{n}\sum_{j=1}^{\rho}\begin{cases} 1 & \text{if } r_{ij} > 0 \\ 0 & \text{otherwise} \end{cases} = \frac{1}{\rho}\sum_{j=1}^{\rho}\mathrm{PCTR}_j \tag{43}$$

where r_{ik} denotes the amount of resource type j required by task i, and PCTR_j denotes the percent of activities that require the given resource type, which gives a column-wise view of RF as follows:

$$\mathrm{PCTR}_j := \frac{1}{n} \sum_{i:=1}^{n} \begin{cases} 1 & \text{if } r_{ij} > 0 \\ 0 & \text{otherwise} \end{cases} \tag{44}$$

RU, the resource use, represents the resource use for each activity, i.e., the number of resource types used. RU varies between 0 and r (the number of resource types). It is a row-wise view of RF ($i = 1, ..., n$) as follows:

$$\mathrm{RU}_i := \sum_{j=1}^{\rho} \begin{cases} 1 & \text{if } r_{ij} > 0 \\ 0 & \text{otherwise} \end{cases} \tag{45}$$

DMND_j is the average quantity of resource j demanded when required by an activity ($j = 1, ..., \rho$) as follows:

$$\mathrm{DMND}_j := \frac{\sum_{i=1}^{n} r_{ij}}{\sum_{i=1}^{n} \begin{cases} 1 & \text{if } r_{ij} > 0 \\ 0 & \text{if } r_{ij} = 0 \end{cases}} \tag{46}$$

RC is the resource constrainedness of each resource type and is calculated as follows:

$$\mathrm{RC}_j := \frac{\mathrm{DMND}_j}{\alpha_j} \tag{47}$$

where α_j is the *availability* of renewable resource type j.

Flexibility impacts on the nonscheduled renewable resource indicators. The nonscheduled resource-related indicators are independent of the schedule. Therefore, they are independent of the rate of flexible dependencies.

All possible structures can be considered a random sample from the maximal structure if the elements of S-SET follow a uniform distribution. In this case, the following formula can be specified:

$$\frac{\mathrm{NRI}(\mathcal{S}) - Exp(\mathrm{NRI}(\mathcal{S}))}{\sqrt{Var(\mathrm{NRI}(\mathcal{S}))}} \sim \Phi(0,1) \tag{48}$$

where NRI($\mathcal{S}$) denotes any mean of the nonscheduled resource indicators, such as RF, PCTR, RU, DMND, and RC for project structure $\mathcal{S}$.

Resource-related indicators for the early schedule. The following indicators from Patterson (1976) require early scheduling ($\overrightarrow{\mathcal{S}}_{\min}$) of the activities regarding the precedence relations but not the resource constraints.

RS is the resource strength of each renewable resource type and is calculated as follows:

$$\mathrm{RS}_j := \frac{\alpha_j - r_j^{\min}}{r_j^{\max} - r_j^{\min}} \tag{49}$$

where α_j denotes the total availability of renewable resource type j, $r_j^{\min} := \max_{i=1,\dots,n}(r_{ij})$ is the highest *individual* resource demand, and $r_j^{\max}$ denotes the peak total demand at any moment for resource type j in the precedence preserving the earliest start schedule.

UTIL_j is the utilization (rate) of resources and is measured based on the critical path length. Higher values indicate more constraints, less room for scheduling, and less possibility of changing the task starting times without increasing the TPT.

$$\text{UTIL}_j := \frac{\sum_{i=1}^{n} r_{ij} t_i}{\alpha_j \cdot \text{TPT}} \tag{50}$$

TCON_j is the constrainedness of (renewable) resource type j over time. In practice, it is the average utilization (UTIL_j) considering only those tasks that use that particular resource type as follows:

$$\text{TCON}_j := \frac{\sum_{i=1}^{n} r_{ij} t_i}{\alpha_j \cdot \text{TPT} \cdot \sum_{i=1}^{n} \begin{cases} 1 & \text{if } r_{ij} > 0 \\ 0 & \text{otherwise} \end{cases}} \tag{51}$$

OFACT_j is the obstruction factor of (renewable) resource type j and is calculated as follows:

$$\text{OFACT}_j := \frac{\int_0^{\text{TPT}} \max\{0; r_j(\tau) - \alpha_j\} d\tau}{\sum_{i=1}^{n} r_{ij} t_i} \tag{52}$$

UFACT_j is the underutilization factor and is calculated as follows:

$$\text{UFACT}_j := \frac{\int_0^{\text{TPT}} \max\{0; \alpha_j - r_j(\tau)\} d\tau}{\sum_{i=1}^{n} r_{ij} t_i} \tag{53}$$

ARLF (average resource loading factor) proposed by Kurtulus and Davis (1982), represents the resource distribution of projects. If resource requirements are in the first half of the project, it has a negative value, while a positive value means that resource demands are rather in the back half of the project, based on the critical path duration of each project. For multiple projects, the possible issue of averaging individual ARLF values is handled by NARLF, where normalization is done with the critical path duration of all projects (Browning and Yassine, 2010b). The formula is further improved by Van Eynde and Vanhoucke (2020) with NARLF', which, on top of this, determines if a resource demand falls in the front or the back based on the portfolio's critical path instead of each project's critical path. It uses two auxiliary variables:

$$Y_{i(\tau)} = \begin{cases} 1 & \text{if activity } a_i \text{ is active at time } \tau, \\ 0 & \text{otherwise} \end{cases} \tag{54}$$

$$Z_{i(\tau)} = \begin{cases} -1 & \text{if } \tau \leq \lceil TPT/2 \rceil, \\ 1 & \text{if } \tau > \lceil TPT/2 \rceil, \end{cases} \tag{55}$$

to get:

$$NARLF' = \frac{1}{TPT} \sum_{\tau}^{TPT} \sum_{i=1}^{n} \sum_{j=1}^{\rho} Z_{i(\tau)} Y_{i(\tau)} \left(\frac{r_{ij}}{|\{r_{ij} : r_{ij} > 0\}|} \right) \tag{56}$$

where τ is the time for the earliest start schedule, considering release dates.

Interval of the scheduled resource indicators. Since the minimax (maximin) structure requires minimal (maximal) resource demands, the following equations can be specified.

$$\mathrm{SRI}_j(\mathcal{S}_{\text{minimax}}) \leq \mathrm{SRI}_j(\mathcal{S}) \leq \mathrm{SRI}_j(\mathcal{S}_{\text{maximin}}) \tag{57}$$

$$\mathrm{SRI}(\mathcal{S}_{\text{minimax}}) \leq \mathrm{SRI}(\mathcal{S}) \leq \mathrm{SRI}(\mathcal{S}_{\text{maximin}}) \tag{58}$$

where SRI_j denotes the scheduled resource indicators, such as RS, UTIL, TCON, OFACT, and UFACT, of resource j, and SNI denotes the mean of a scheduled resource indicator of all resource types.

Aggregated indicators. Since the number of resource demands is very heterogeneous, the mean of the resource indicators was considered instead of calculating these values of all resources. Moreover, when the resource numbers differ across projects, the means of these indicators were used to ensure the comparability of the resource indicators. Similarly, for time related indicators, the focus is also on the means. In the following, the means are denoted without indexing.

To represent the distribution of the same indicator calculated for multiple projects, an alternative to using average values or multiproject specific formulas is the α-distance (Labro and Vanhoucke, 2008). Its value ranges from 0 (no variation) to 1 (maximal variation). For a vector of arbitrary nonnegative values $X = (x_1, \ldots, x_n)$, $\overline{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$ it is calculated as: $\alpha^{dist} = \frac{\sum_{i=1}^{n}(|\overline{x} - x_i|)}{\alpha_{max}^{dist}(x_{min}, x_{max})}$, where x_{max} is the upper, x_{min} is the lower bound of values of X.

$$\begin{aligned} \alpha_{max}^{dist}(x_{min}, x_{max}) =& (x_{max} - \overline{x}) \left\lfloor \frac{\sum_{i=1}^{n} x_i - n \cdot x_{min}}{x_{max} - x_{min}} \right\rfloor \\ &+ \left| x_{max} - \overline{x} + (\textstyle\sum_{i=1}^{n} x_i - n \cdot x_{max} \mod x_{min} - x_{max}) \right| \\ &+ (\overline{x} - x_{max}) \left(n - 1 - \left\lfloor \frac{\sum_{i=1}^{n} x_i - n \cdot x_{max}}{x_{max} - x_{min}} \right\rfloor \right) \end{aligned} \tag{59}$$

Gini coefficient (Gini, 1936) is used in economics to measure inequality across a population. Van Eynde and Vanhoucke (2020) used it to show how the total work content (each activity's resource demand multiplied by it's duration) is distributed amongst all activities. Value 0 means all activities have the same work content (equality), and 1 means only one activity has all the work (inequality).

$$G = \frac{1}{n}\left(n+1-2\left(\frac{\sum_{i=1}^{n}(n+1-i)[WD]_i}{\sum_{i=1}^{n}[WD]_i}\right)\right) \tag{60}$$

for a population of $WD = \sum_{j=1}^{\rho}([RD]_j \cdot TD)$, $[WD]_i$ $(i = 1, ..., n)$ is a column vector, indexed in a non-decreasing order $([WD]_i \leq [WD]_{i+1})$.

3.3 Applied multivariate analysis

In addition to the descriptive statistics, multivariate and network analyses were used to explore the relationships between the indicators. First, a correlation graph is specified between the indicators, represented by nodes, where the arcs represent the strength of the correlation between these nodes. The clustered correlation graph collects subsets of highly correlated indicators and groups them into a module by the Leiden method (Traag et al., 2019). In addition, the Force Atlas II (FA2) algorithm (Jacomy et al., 2014) arranges central indicators, which have many correlations between other variables, to the center of the module, and peripheric indicators are arranged at the edge of the correlation graph. For regression, robust statistical methods are applied such as the quantile regression (Koenker and Hallock, 2001) or the generalized least squares method (Aitken, 1936).

3.4 Proposed metaheuristic optimization framework

To schedule a multiproject, the resource-constrained multiproject scheduling problem (RCMPSP) (Pritsker et al., 1969) needs to be solved. It is a generalization of the well-known RCPSP problem (Dike, 1964) that is already proven strongly NP-hard (Lenstra and Rinnooy Kan, 1978). Due to the complex nature of these problems and a large number of activities and high resource-constrainedness, this study considers a metaheuristic optimization in line with the literature to achieve approximate best solutions without the need for high and time-consuming computation efforts using the exact mathematical models. The model for this study's proposed metaheuristic optimization framework is implemented in a simple spreadsheet environment that managers are also familiar with. The simulations use the commercial optimization engine OptQuest$^{\text{TM}}$, which combines metaheuristic procedures including scatter search, tabu search, and neural networks (Laguna, 2011). Researchers widely use the tool, but one of the limitations is that due to commercial reasons, the details of the composite methods of the tool remain a black box (Kleijnen and Wan, 2007).

For comparison with other popular software, refer to Eskandari et al. (2011) and Jafferali et al. (2005). The proposed simulation framework addresses both single and multiple projects, multiple global and local resource types (Hartmann and Briskorn, 2021), release dates, multiple execution modes for demands such as time, resource and cost, stochastic activity durations and release dates, as well as overtime costs, pre-defined and customizable objective functions and constraints. With the graphical part of the user interface it is also possible to visualize and compare the resource profiles of two separate multiproject schedules, the durations of the portfolio by subprojects and the cost profile. In this dissertation, only a subset of these features will be used and demonstrated for the case study.

3.5 Applied sensitivity analysis

A Monte Carlo sensitivity analysis was designed to simulate many project outcomes using the modeled spreadsheet logic within the simulation framework. Using this method a challenging full-factorial enumeration of the parameter combinations was not necessary. The sensitivity analysis was applied to the company project plan of the case study to show, understand and validate the effects of flexibility for a real project plan in a representative context. The study analyzed the usual results when varying two key input parameters: the flexible dependencies and the completion priorities given to supplementary tasks. Random values were generated for the actual probabilities defined in the real project plan, to explore further how these input parameters influence the probabilities of the outcomes such as the time needed to complete the project's and the portfolio's duration (TPT), also measuring the contribution to them.

Chapter 4

Simulation results

4.1 Descriptive statistics and data comparison

Table 7 shows the number of projects in the 12 datasets of the 7 project databases.

TABLE 7: Descriptive statistics of the applied project databases

(a) Descriptive statistics of the single project databases

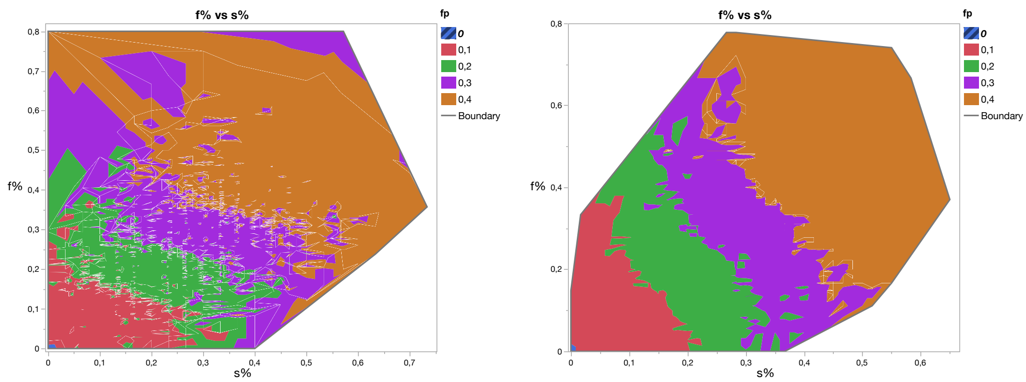
			Task number mean ($\bar{I}_1$)				
			original	minimal structures			
Database	Set	N	fp=0	0.1	0.2	0.3	0.4
Boctor	Boctor	2160	75.00	67.38	60.09	52.40	44.81
Kolisch	SMCP	1800	29.00	26.16	23.29	20.51	17.40
	SMFF	4320	30.00	26.97	23.84	21.08	17.77
MMLIB	MMLIB50	4860	50.00	45.05	40.14	35.18	29.86
	MMLIB100	4860	100.00	89.94	80.00	70.10	59.97
	MMLIB+	29160	75.00	67.50	60.05	52.54	44.85
Patterson	Patterson	990	24.02	21.73	19.51	16.85	14.91
PSPLIB	j30	5760	30.00	27.14	24.08	20.86	17.91
	j30sm	4320	30.00	27.06	24.02	21.11	17.78
Real-life	PROTRACK	1125	65.56	58.83	52.09	45.50	39.78
RG	RG30	16200	30.00	26.96	24.07	21.08	18.01
	RG300	4320	300.00	270.16	240.11	210.25	180.31

(b) Descriptive statistics of the multiproject databases

			Mean of task numbers (by projects) ($\bar{I}_1$)				
			original	minimal structures			
Database	Set	N	fp=0	0.1	0.2	0.3	0.4
BY	BY	110880	60.00	53.99	47.98	42.04	35.94
MPLIB1	Set 1	7497	360.00	324.08	287.95	251.59	216.39
	Set 2	13167	720.00	648.13	576.42	503.87	431.86
	Set 3	20286	1440.00	1296.34	1151.50	1007.89	863.79
MPLIB2	Set 1	91125	1000.00	900.19	800.08	700.10	599.91
	Set 2	77760	1000.00	900.40	800.39	700.30	600.16
	Set 3	77760	1000.00	900.01	799.77	700.09	599.89
	Set 4	69120	1000.00	899.88	800.25	700.17	600.29
MPSPLIB	MPSPLIB	1260	872.14	785.12	698.91	610.79	522.21
RCMPSPLIB	RCMPSPLIB	234	164.62	149.00	131.65	117.15	98.38

The total considered project number in a single project database was $79,875$. This value was nine times more than the original 8,875 projects. This result is due to the inclusion of both minimum and maximum structures in the database with four different flexibility parameter (fp) values. Most projects were derived from the MMLIB+ dataset (29,160) from the MMLIB database and the RG30 dataset from the RG database (16,200). The average task number within a project in the original databases was between 24 and 300 (see column $fp = 0$ in Table 7); this value decreased for minimal structures when the flexibility parameter (fp) was increased. The considered multiple project database contains 5 databases and 10 datasets. Considering demands by projects shows the same effects of increasing flexibility. Nevertheless, this database does not contain any real-life data; therefore, only simulated projects can be compared.

Figure 15 shows the relationship between the specified rate of constraints and the observed rates of the supplementary tasks and flexible dependencies.



(a) Single projects (b) Multiple projects

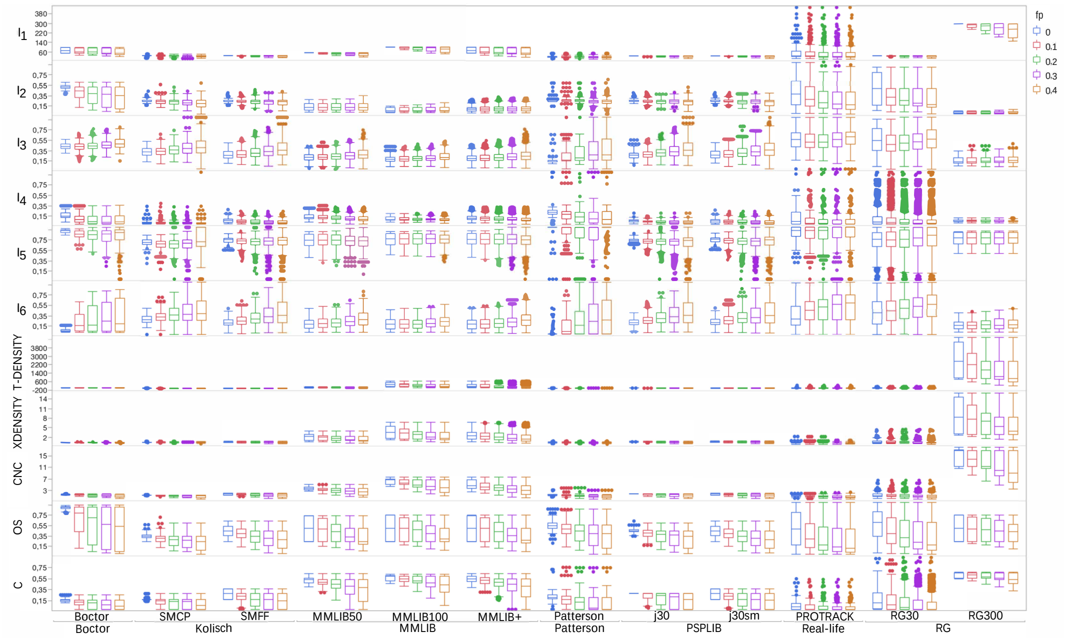
FIGURE 15: Observed rate of the supplementary tasks (s%) and of the flexible dependencies (f%) by the flexibility parameter rate (fp)

fp is maximized to 40% for both theoretical and practical reasons. However, the expected value of f% and s% is 40% if fp% is 40%, which is in line with the guide of the DSDM (see Figure 11), Fig 14 indicates that a further increase in the fp% above 40% might cause all tasks to be flexible and could be omitted or postponed in the minimal structure in which only mandatory tasks are completed. In addition, since we consider an iteration (sprint) as a logic plan, the number of flexible tasks may be higher than 40%. However, on average, this number should not be greater than 40%. In the case of hybrid projects, the number of flexible tasks is less than that in agile ones; therefore, fp between 0.0 to 0.4 well simulates the traditional-hybrid-agile transitions.

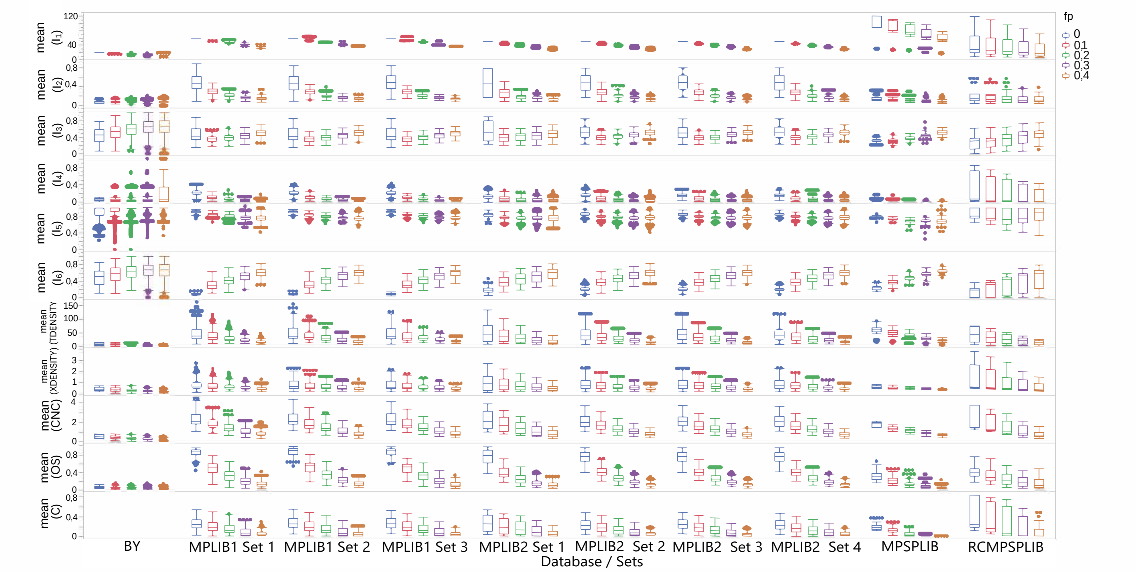
Figure 15 shows that the observed rates of the supplementary tasks and those of flexibility dependencies covered the most combinations of the flexibility parameters.

4.1.1 Flexibility effects on the indicators

Figure 16 compares the structural indicators in the 22 datasets with 5 different flexibility parameters. The statistical differences for each indicator between the different flexibility levels in each database are also examined and provided with a summary table. The companion tables for each boxplot (Figure 16 - 19) can be found in Appendix B (Tables 15 - 19).



(a) Single project database



(b) Multiple project database

FIGURE 16: Flexibility effects on the structural indicators

Figure 16 shows that the considered datasets provide various complexity values. Regarding most complexity measures, such as $I_1 - I_6$, OS, and C, the real-life database covers the greatest intervals of the structure-related and complexity-related values, while regarding the CNC, T-DENSITY, and X-DENSITY indicators, the RG300 datasets cover the most possible values. Nevertheless, the flexibility generally extends to the covered intervals of the structural indicators in all datasets. Yet, the multiple project databases do not contain real-life datasets. Thus, the comparison between the simulated and real-life database can only be analyzed in a single project database.

Figure 17 compares the time-related indicators of projects from the 7 single project databases and 12 datasets.

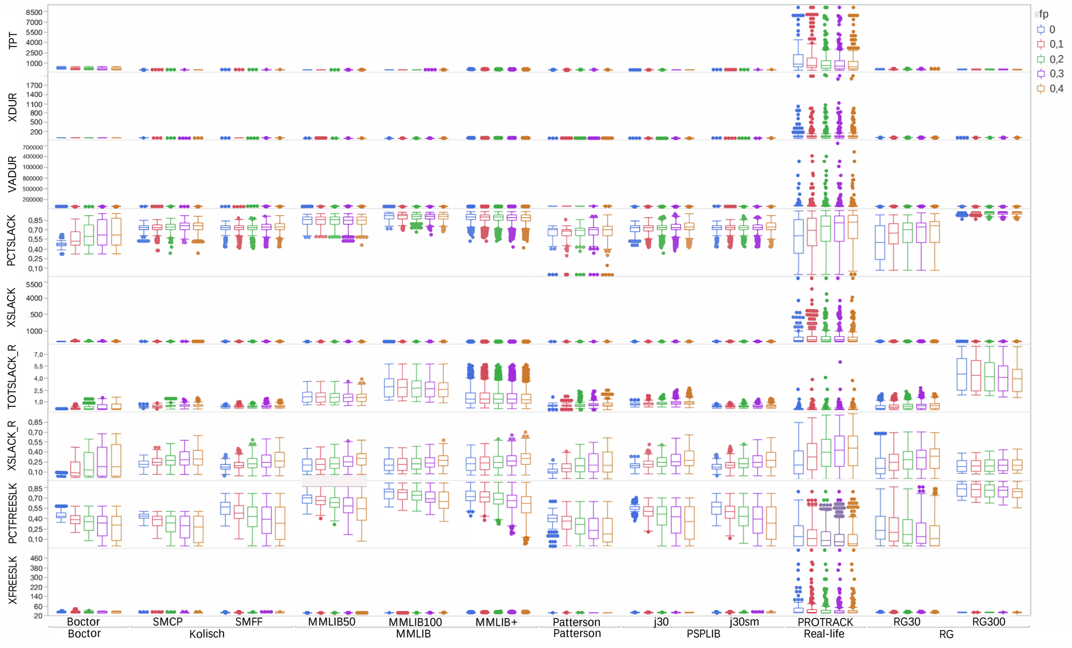


FIGURE 17: Flexibility effects on the time-related indicators

Figure 17 also shows that the real-life database and the RG300 dataset covered the most possible values of the time-related measures/indicators. Nevertheless, despite the spread of the time-related value intervals induced by considering flexibility, the real-life database covered significantly more possible values for the time-related indicators. Without considering flexibility, any single simulated database focuses on a narrow interval of time-related indicators that can be very far from real-life project values.

Figure 18 compares the project resource-related indicators from the 7 databases and their 12 datasets.

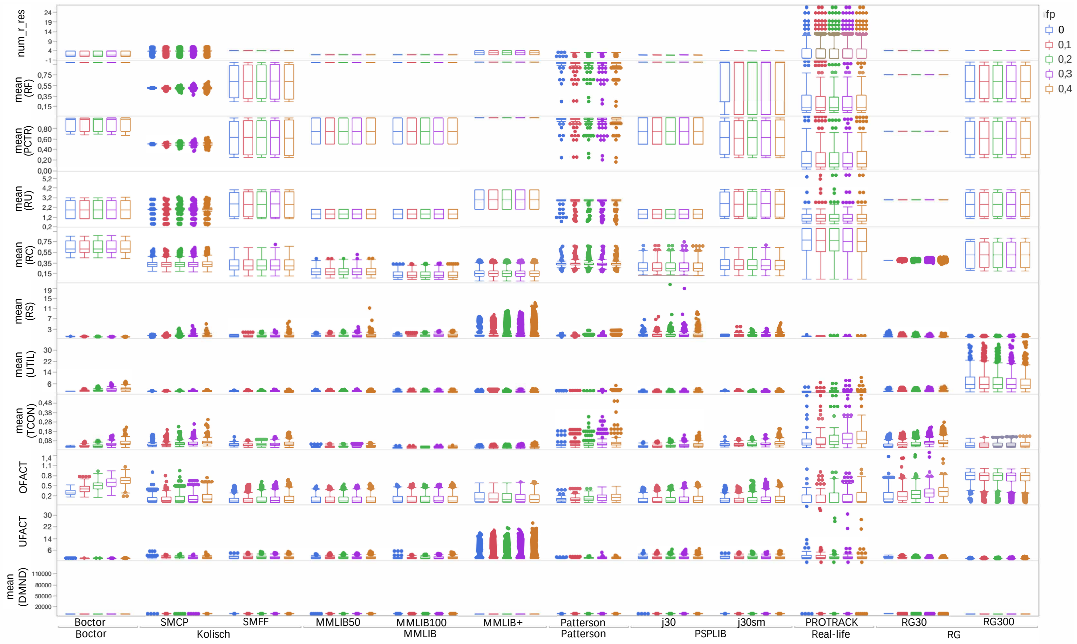
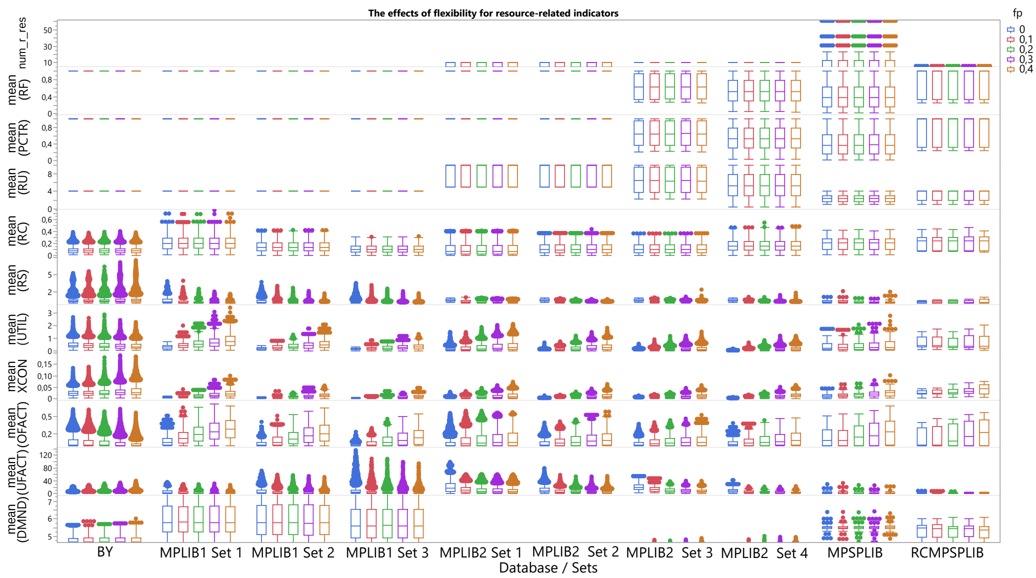


FIGURE 18: Flexibility effects on the resource-related indicators

The difference between the simulated and real-life projects based on the resource-related indicators can also be identified in Figure 18. Nevertheless, in contrast to the time-related indicators, Figure 18 shows that the MMLIB+ dataset provided resource-related indicator values, e.g., the resource strength (*RS*) values, that never occur in a real-life project. For example, the number of resources (*num_r_resources*), resource constrainedness (*RC*), and underutilization factor (*UFACT*) values varied in a wider range in the real-life database. In all cases, by introducing flexibility to the project structures and including the generated minimal structures, the interval of the possible values of the structure-related, time-related, and resource-related indicators can be widened and brought closer to the values of the real-life database. The interpretation ranges of the indicators of multiprojects are also broadened, see Figure 19.

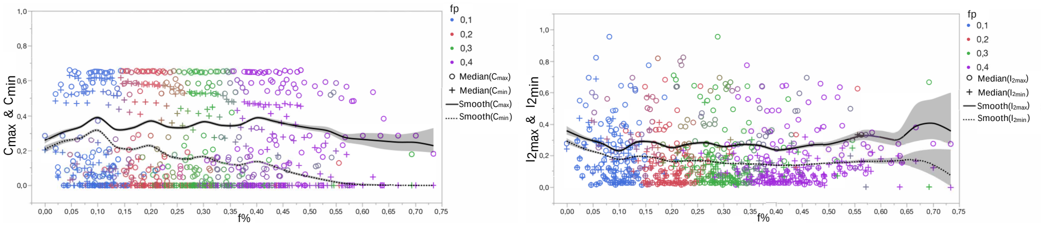
(a) The effects of flexibility for time-related indicators on multiprojects



(b) The effects of flexibility for resource-related indicators on multiprojects

FIGURE 19: Flexibility effects on the demand-related indicators among multiprojects

Figure 20 compares the complexity (C) and parallelization (I_2) values of the minimal and maximal structures regarding the ratio of flexible dependencies ($f\%$) (marked on the horizontal axis).



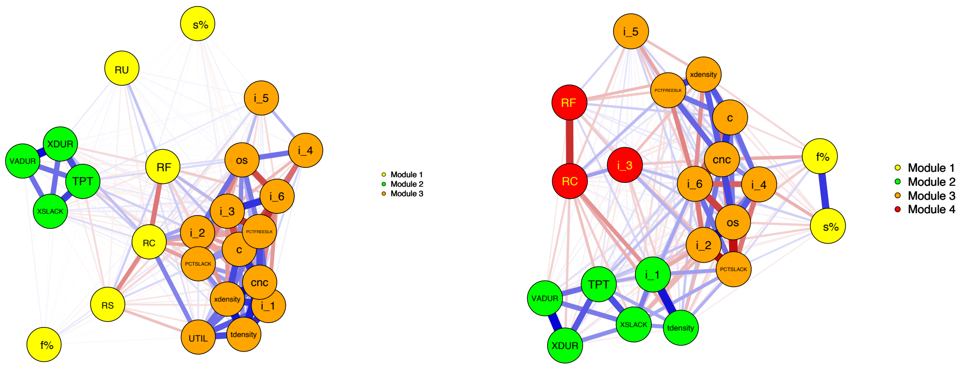
(a) Flexibility vs complexity (b) Flexibility vs parallelization

FIGURE 20: Structural changes in complexity and parallelization

Figure 20 shows that when the flexibility parameter (fp) was increased via an increase in the rate of flexibility dependencies ($f\%$) for the minimal structures, the complexity (C) decreased (see Figure 20(a)), as did the serial completions (see Figure 20(b)).

4.1.2 Flexibility effects on indicator interdependence

Figure 21 shows the clustered correlation graph between the indicators in the single-project database. Pearson's correlation coefficient was applied to determine the correlation graph. Grouping was accomplished using the Leiden modularity-based community detection method. In the center of the modules are the indicators that correlate with most other indicators. On the periphery are the indicators correlated with relatively few other indicators, and their correlations with the remaining indicators are weak.



(a) For the simulated projects (b) For the real-life database (RS, $UTIL$ cannot be used in correlation graph)

FIGURE 21: Clustered correlation graphs between the indicators[1]. Notes: the correlation strengths are proportional to the tightness of the arcs between the nodes. The blue (red) arcs indicate positive (negative) correlations.

[1]Only the significant correlations are represented. Leiden's modularity specified the modules. The nodes are represented only where there is variance.

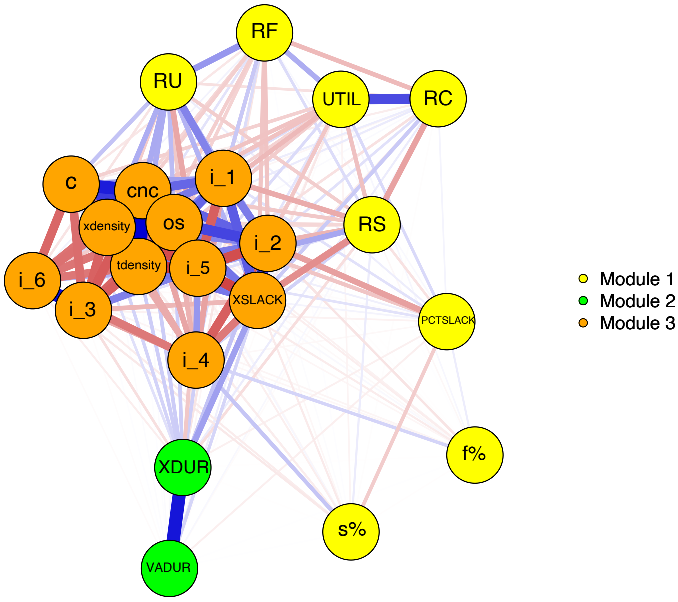


FIGURE 22: Clustered correlation graph of the multiple project database indicators. Note: indicators represent average values.

One interpretation of Figure 21 is that several redundant indicators were highly correlated with each other. This was especially true for the topological indicators (Module 3). In comparison, the proposed ($s\%, f\%$) flexibility indicators were located on the periphery and in another module (i.e., in Module 2), which suggests that, although they are related to the other indicators, they should not be merged with them. The other finding is that the modules in the simulated datasets were quite well provided with the structure-related, time-related and resource-related indicators, where the complexity (C), resource constrainedness (RC), and project duration (TPT) played central roles. At the same time, the real-life dataset provided more mixed modules. Thus, the correlation direction did not change, four modules were specified, and at least one structural indicator was included in all the modules, which indicates the greater importance of structural indicators in real-life projects. The separation of the three modules can also be considered in the case of multiple projects (see Figure 22). When Figures 21 and 22 are compared, more significant differences can be seen between the simulated vs. real-life indicators than between the single vs. multiple project indicators. The multiple project database also produced three modules. Nevertheless, they were more mixed than were the single-project cases.

Similar results were obtained using the nonparametric Kendall's rank correlation method (Gorrostieta and León, 2019; Kendall, 1938) to explore possible nonlinear relationships between the indicators further. The corresponding results can be found in Appendix B, in Figure 40 for single artificial and real projects, and in Figure 41 for multiple project databases. The same number of modules was specified, having slight differences. In general, the indicators within time-related modules became less connected, while the members of resource-related modules got closer connected compared to the parametric version. For single and multiple projects, $f\%$ and $s\%$ became more related to structural indicators and remained close to the resource-related module. For real-life projects, resource-related indicators are more isolated and the connection with the structural module is less emphasized than in the parametric case.

Flexibility considerations not only expand the interval of the indicator values but also specify new value pairs for the coupled indicators. Figure 23 shows the effect of including minimal structures on the complexity and time-related indicators. The blue circles and plus signs represent the original pairs of indicator values in all subfigures. Figure 23 shows the pairs of the indicator values of the total slack ratio (TOTSLACK-R) and average slack ratio (XSLACK-R) as time-related indicators on the vertical axis and complexity (C) and parallelization (I_2) as structural parameters on the horizontal axis.

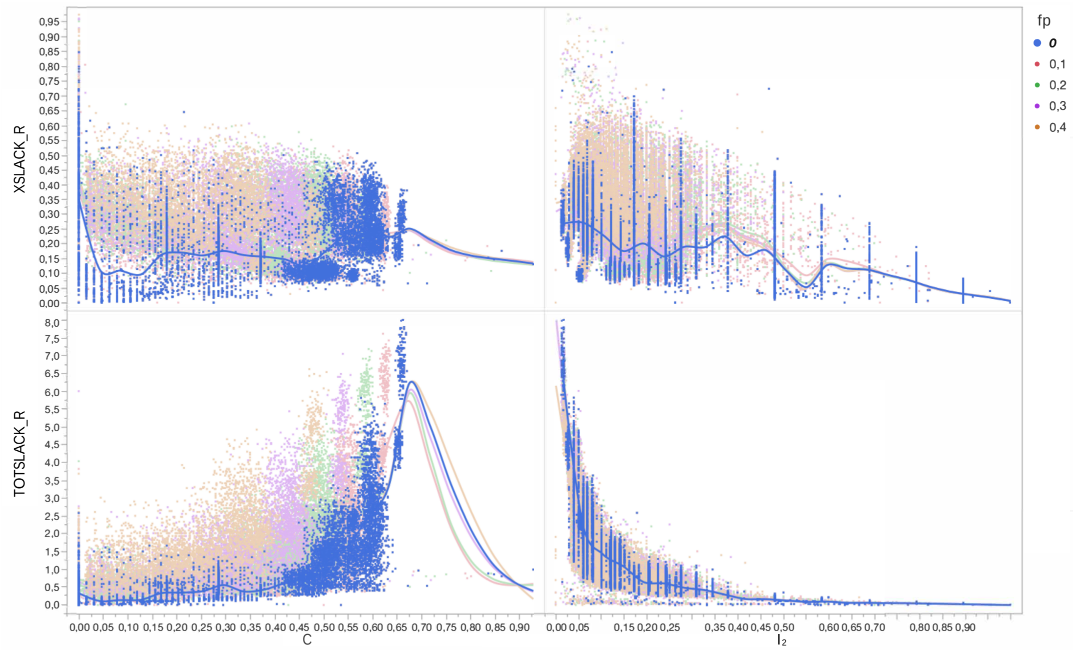


FIGURE 23: Flexibility effects on the relations between the time-related and complexity indicators

Figure 23 shows that including minimal structures helps explore new areas on the planes spanned by the structure-related and time-related indicator pairs. These combinations better cover the area of the possible value pairs. Flexibility can also be expressed in other ways as follows: the minimal structures of flexible projects have higher average slacks, which can be better utilized in resource allocation. When the minimal structures of flexible projects are included, the domain is better covered if a combination of (1) resource-related indicators, such as the mean of resource constrainedness ($\overline{\text{RC}}$)/the mean of the obstruction factor ($\overline{\text{OFACT}}$, and (2) a structural indicator, such as complexity (C)/parallelization (I_2), is studied (see Figure 24).

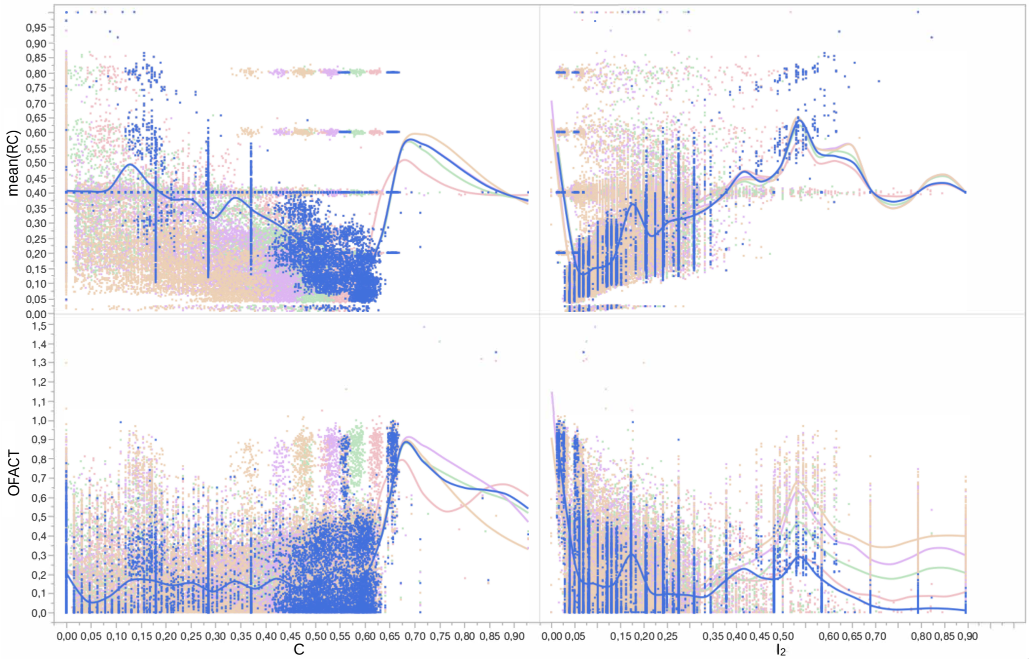


FIGURE 24: Flexibility effects on the relations between the resource-related and complexity indicators

Figure 24 shows that while minimal structures decreased the complexity (C) and increased the parallelization (i.e., decreased serialization) (I_2), they also increased the obstruction factor and the resource constrainedness.

Figure 25 shows that flexible multiprojects become more parallel and slack times increase while their overall complexity is reduced. As a result, total project time is also reduced, and resources get more constrained – the interval of indicator values for parallelity and complexity shrinks and shifts to lower values considering minimal structures.

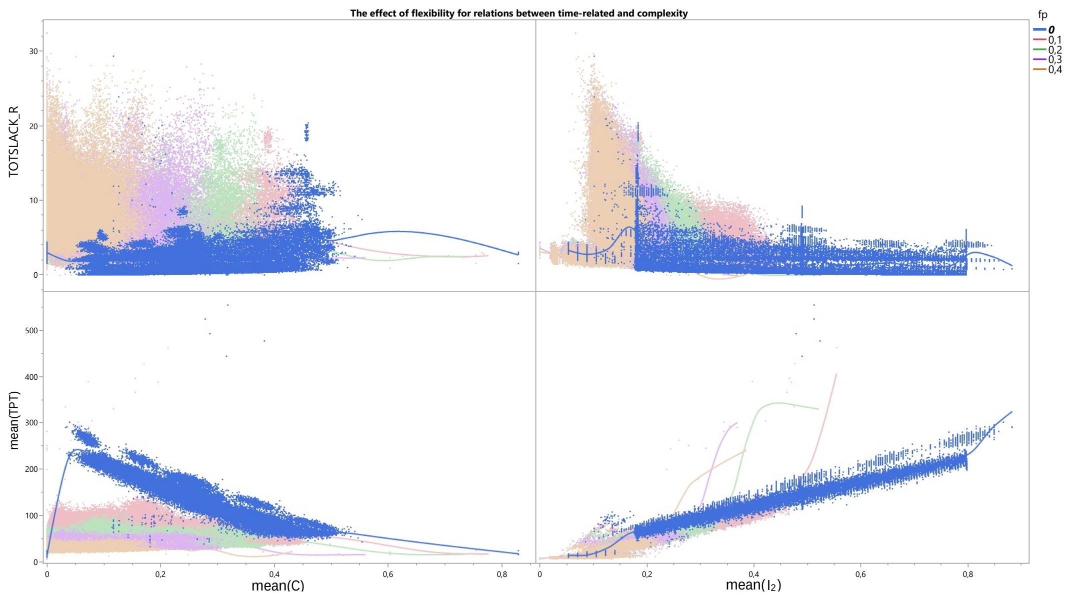


FIGURE 25: The effect of flexibility for relations between time-related and complexity indicators for multiprojects

Figure 26 shows the relations between the slack ratios (TOTSLACK-R, XSLACK-R) and the resource-related indicators in the earliest start schedule. Considering the minimal structures of flexible projects increases the slack ratio, the resource constrainedness, and the obstruction factor because of the parallelization. These combinations of time-related and resource-related indicator values occurred only in flexible project plans.

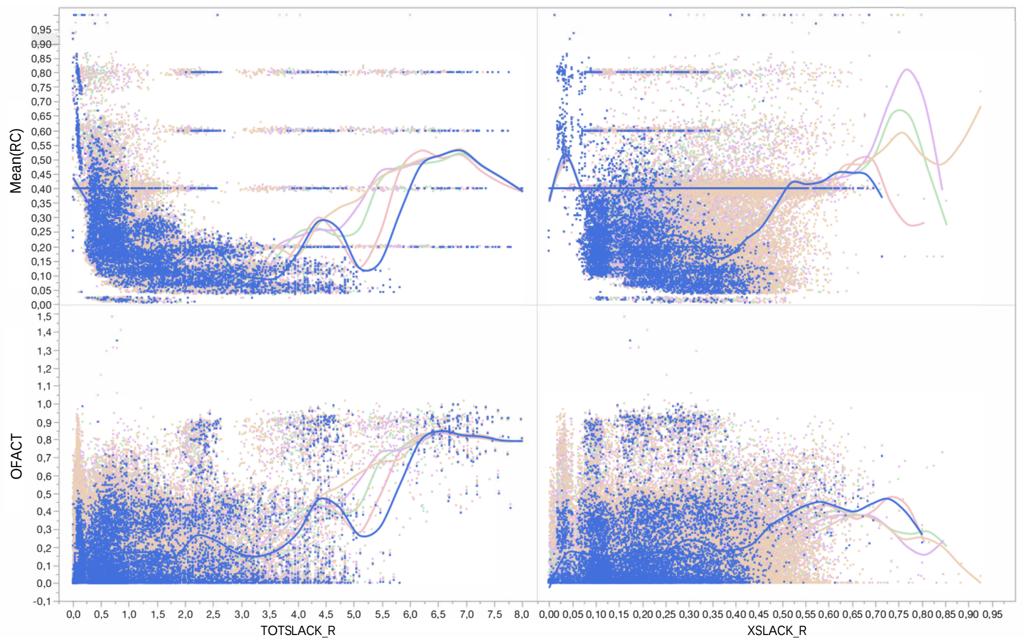
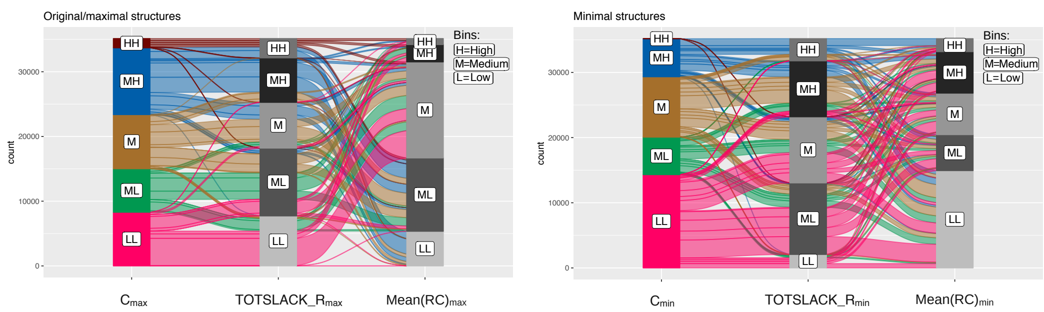


FIGURE 26: Flexibility effects on the relations between the time-related and the resource-related indicators

Figure 27 shows the mutual effect of flexibility on a structure-related (C), a time-related (TOTSLACK-R), and a resource-related (RC) indicator. Flexibility can reduce complexity (compare Figures 27(a) and (b)) while it increases the slack ratios and reduces the resource constrainedness (RC).



(a) Original/maximal structures (b) Minimal structures

FIGURE 27: Alluvial diagrams[1] of the complexity, time-related, and resource-related indicators

Figure 28 depicts structural and resource-related indicators and gives insight into their variation on multiple levels: tasks, connected components, and projects. Variation in parallelity described by $\alpha^{dist}(I_2)$ gets closer to one (less variation) when flexibility is present and varies more when only a few projects exist.

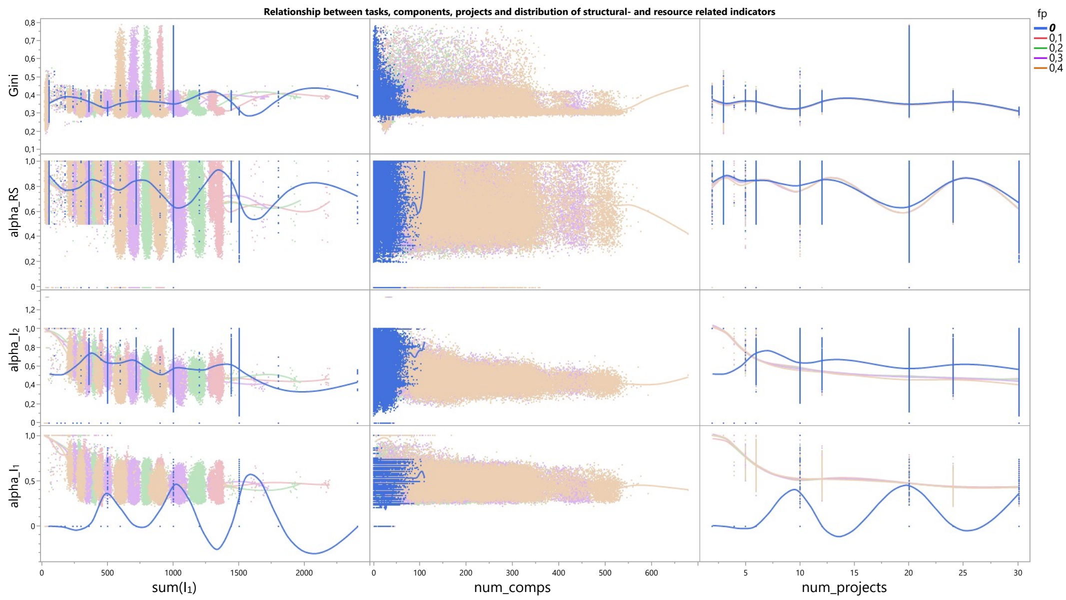


FIGURE 28: The effect of flexibility for distributions of structural and resource-related indicators on multiple levels

With increasing flexibility for minimal structures, the values of the Gini index become smaller as the work demand for resources gets more equally distributed (closer to zero) amongst projects. However, the interval of Gini indices also widens, which means a higher potential inequality in some cases. $\alpha^{dist}(RS)$ shows less variation (closer to zero) in the resource demand and availability relation when flexibility is higher. $\alpha^{dist}(I_1)$ shows that the variation in the number of tasks decreases with more projects present.

4.1.3 Flexibility effects on multiple modes

Evaluation for multiple modes is only possible for artificial single projects. MMLIB+ has the highest number of modes (9) and the amount normally varies from 3 (MMLIB50 and MMLIB100, J30mm) to 4 execution modes (as in Boctor). The modes usually have different meanings regarding resource- or time demands. For example, work content distribution gets more inequal (*Gini* indicator) for modes with a higher index in the Boctor dataset, and the opposite is true for the other group of datasets examined. Boctor has a unique meaning for mode numbers and cannot be easily ordered by meaning. For other datasets, the resource constrainedness (RC) gets higher with lower mode indices, and TPT decreases as a trade-off, shown in

[1]Variables are transformed and cut into five bins, labeled 'LL' (low-low), 'ML' (medium-low), 'M' (medium), 'MH' (medium-high), 'HH' (high-high).

Figure 29. Similarly, a lower mode index means lower task durations and decreased slacks.

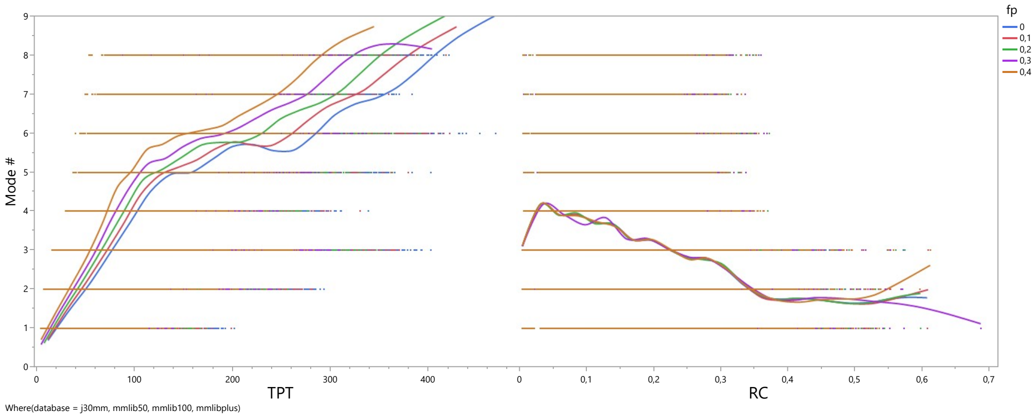


FIGURE 29: Trade-off between time- and resource demands of the different execution modes

It is visible in Figure 44 that $NARLF'$ is increasing in general and resources get from front-loaded to more evenly distributed along the project with higher modes. All related Figures can be found in Appendix B.

4.1.4 Flexibility effects on resource load on different levels

The effects of flexibility can also be visualized on the different topological levels such as tasks, sprints (represented by sets of activities) and projects. Figure 30 shows the decreasing TPT and also a decreasing number of (supplementary) activities for the multiproject databases. At the same time, the sets of activities in the network that are linked to each other, i.e., the number of connected components (Thulasiraman and Swamy, 2011) increases as a result of flexible dependencies being removed. The same decrease can also be observed by looking at the project level.

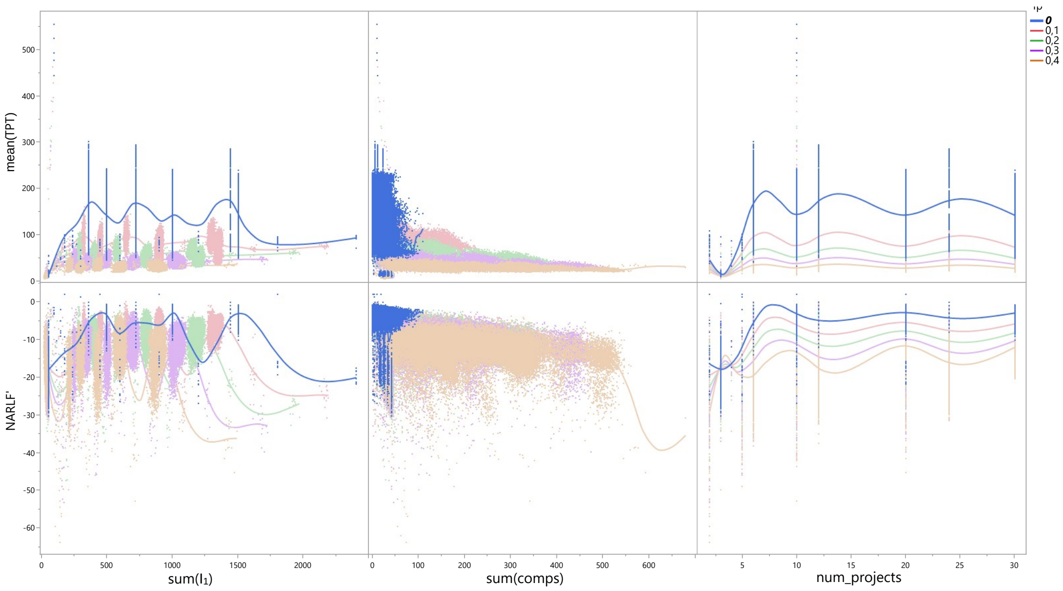


FIGURE 30: The effect of flexibility for resource loading ($NARLF'$) and total project time (TPT) on multiple topological levels

4.1.5 Flexibility effects on total project time

Besides existing descriptive statistics, the relationship between flexibility and project duration was further explored. Additionally, a regression model was considered and summarized in this section.

As non-normality and violation of the homogeneity of variances were found during the verification of assumptions, robust methods were applied. Further analysis details are given in Appendix D.

For single projects (excluding real-life database), Spearman's rank correlation shows a statistically significant, moderate, negative relationship between fp and TPT ($\rho = -0.405, p - value < .001$). For multiprojects, the relationship between fp and TPT is negative, moderate in strength ($\rho = -0.573$), and statistically significant ($p - value < .001$).

Using quantile regression, the pseudo-R-squared (Koenker, 2005) value for single projects is only $R1 = 0.09$, showing a weak effect size. For multiprojects, the pseudo-R-squared is $R1 = 0.465$, which can be considered a moderate effect size in the field of this study ($p - value < .001$).

4.1.6 Flexibility effects on variation in total project time

The statistical measure of variance was used to calculate and compare how flexible methods affect total project times (TPT) compared to traditional methods in the available groups of databases. The database groups were the artificial single projects, real single projects, and artificial multiprojects. First, the variances were calculated for each flexible case (represented by $fp = \{0.1, 0.2, 0.3, 0.4\}$) relative to the traditional methods (represented by $fp = 0$) within each database group. To make these results comparable between the different groups of databases, the coefficient of variation (CV), also known as relative standard deviation shows the extent of variability in relation to the mean of the population. The higher the CV, the greater the dispersion. Table 8 shows the actual values of each descriptive statistic, including the measure CD, that is, the coefficient of dispersion (also known as variance-to-mean ratio) additionally.

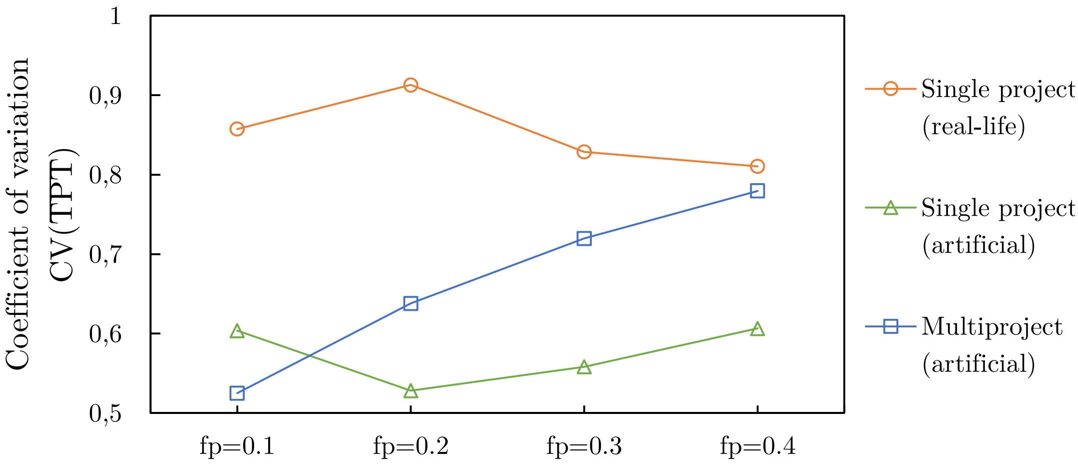


FIGURE 31: The coefficient of variations of average total project time by flexibility parameters of different database groups

As Figure 31 shows, artificial multiproject databases have the lowest initial variation for average total project time and it is similar to artificial single projects. Real-life single projects have a relatively high initial variation compared to artificial single and multiprojects. While the variation of multiprojects average total project time continuously increases, the shape of single projects (including both artificial and real-life) seems inconclusive.

TABLE 8: Data of TPT related descriptive statistics

	Single project artificial				Single project real				Multiproject artificial			
fp	0.1	0.2	0.3	0.4	0.1	0.2	0.3	0.4	0.1	0.2	0.3	0.4
StDev	40.06	35.04	37.04	40.24	1417.33	1508.98	1369.91	1339.48	61.08	74.18	83.73	90.68
Var	1604.64	1227.64	1372.05	1619.24	2008816.47	2277015.01	1876663.52	1794203.99	3730.63	5502.92	7010.83	8222.70
CV	0.60	0.53	0.56	0.61	0.86	0.91	0.83	0.81	0.53	0.64	0.72	0.78
CD	24.18	18.50	20.68	24.40	1215.30	1377.56	1135.35	1085.47	32.07	47.30	60.27	70.69

Chapter 5

Discussion

5.1 Evaluation of the project library comparison

Two error types can be made when testing project scheduling and resource allocation algorithms only in simulated databases. The first problem is whether new algorithms are applied to real-life projects that have different types of complexity (see Figure 16), time-related (see Figure 17), or resource-related (see Figure 18) indicator values compared to simulated projects in (benchmark) databases. Even if scheduling simulated projects is more difficult for the current objectives and algorithms, these algorithms may not be prepared for the challenges of the new objectives often found in real-life projects. Creating a specified database tailored to one type of problem can cause discrepancies in real-life usage because of indirect constraints rooted in unconsidered properties. Second, if the algorithms are optimized to properties of simulated projects that never appear in real life, resources are wasted. An interesting result is that the differences in the indicator values are much larger between simulated and real-life projects than they are between individual and multiple projects (compare Figures 16-18 and Figures 19(a-b)). The relationship between the indicators illustrated by the clustered correlation graph (see Figures 21 and 22) also shows significantly different results, mainly between the simulated and real-life projects. In the current research, it was not possible to include a real-life multiple project database as there is no such library available at the time of this dissertation, however, it is essential to examine real-life projects. The simulated datasets should also be combined because an individual dataset usually covers only a small range of an indicator (see Figures 16-18).

Figures 16-18, 19 also show that including minimal structures (see Figure 13) has widened the indicator intervals; therefore, even if flexible structures are not studied, the extended dataset may cover larger indicator intervals.

Table 9 compares the simulated and real-life databases. The indicators from the two groups, i.e., (1) a real-life database and (2) simulated datasets, were compared by an ANOVA. Table 9 shows the number of indicators with significantly different values between these groups.

TABLE 9: Number of significantly different indicators between the simulated and the real-life databases ($p - value < 0.001$)

Indicators	$fp = 0$	$fp = 0.1$	$fp = 0.2$	$fp = 0.3$	$fp = 0.4$	All
Structural	11/13	11/13	10/13	10/13	11/13	11/13
Time-related	9/9	9/9	9/9	9/9	9/9	9/9
Resource-related	9/11	8/11	8/11	8/11	8/11	8/11

When flexibility and generating minimal structures are considered, the indicator interval can be widened; therefore, this operation should be covered in the testing of project scheduling or a resource allocation algorithm to widen the scope of the application of that algorithm. Nevertheless, considering minimal structures does not solve the problem that most complexity, time-related and resource-related measures remain significantly different between the real-life and simulated databases.

Figure 20 shows that increased flexibility reduces complexity and increases parallelization (decreases the task sequence length). These results are in line with the requirements of flexible project management approaches for reducing project complexity (Williams, 2010). However, Figure 21(a) shows that structural flexibility correlates with the resource-related indicators, especially in the simulated databases where resource constraints are prespecified. In real-life projects, structural flexibility forms a separate module. In contrast to the simulated projects, the structural flexibility indicators mainly correlated with the other structural and topological indicators; because of the lack of resource constraints, indicators RS and UTIL could not be calculated.

5.1.1 Flexibility effects on demands

Considering flexibility widens the indicator intervals and specifies new demand combinations. Figures 23-26 indicate that including minimal structures of flexible projects covered more of the domain. The new combination of indicators specified new structures that have never been tested by project scheduling and resource allocation algorithms. However, the fact that flexible projects are becoming increasingly popular implies that tasks must be prioritized and technological dependencies must be rethought. Projects supporting multiple modes can exploit a higher degree of flexibility due to alternative decisions on how the different trade-offs between time, resource or cost are varied. Indicator values of multiprojects are more sensitive to changes in structural flexibility, especially for the duration. The results shown in Figure 31 are in line with literature (Dybå and Dingsøyr, 2008), suggesting that agile multiprojects become less predictable in terms of duration (and planning) from the perspective of other projects, or the organization itself, when flexibility is increased. Minimal structures have the advantage of eliminating the need to use new algorithms. Existing algorithms can be tested in new structures generated by the FSG. Nevertheless, maintaining flexibility values, flexible project planning and scheduling algorithms can also be tested in a large set of project databases.

Chapter 6

Validation and verification

6.1 Case study - Continental Automotive

Due to the limited amount of theoretical and empirical studies related to flexible projects, a single case qualitative case study methodology (Yin, 2009) was chosen to support the quantitative research.

The case study took place at Continental Automotive Ltd. research & development center, in Hungary. The location has (among others) many projects for electronic brake systems, including software development. The case was selected because the organizational structure, type, and applied methodology of the location's projects are highly relevant to the dissertation's topic, and the access to empirical data and professionals provided a good basis for research.

6.1.1 Company overview

Continental is a multinational automotive supplier company founded in 1871, specializing in brake systems, interior electronics, automotive safety, powertrain and chassis components, tires, and many other parts for automotive. Figure 32 shows the actual structure and key data of the organization. Continental is present today in 58 countries with a generated sales of €33.8 billion and employs around 190.000 people. The scope of this case is electronic brake systems, where Continental is a first-tier supplier with typical competitors like Bosch and ZF Group.

6.1.2 Context of projects

The organization is considered project-based as an external contributor for various clients. It has a matrix-like structure (a mixed organizational form with vertical hierarchy overlaid by lateral authority, influence, or communication (Knight, 1976) with distributed locations with several projects forming a multiproject setting. The traditional V-model (Forsberg and Mooz, 1991) is used for safety-critical embedded software development which is mixed with agile methods, such as a slightly modified version of Scrum sprint. The company is actively seeking ways to adopt agile practices for its software development activities.

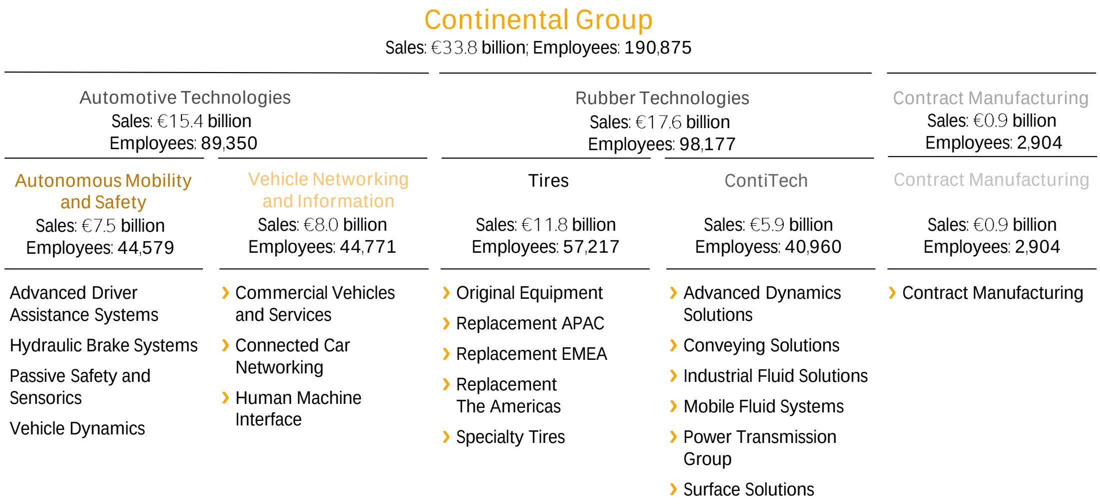


FIGURE 32: Overview of Continental group
Source: *Continental Annual Report* (2021)

6.1.3 Data collection and analysis

Data was collected with access to primary data (experts on different levels) and secondary data (project plans, manuals or other work products, intranet, ticketing database, and version control system).

An empirical multiproject plan was selected to realistically represent the set of simultaneously running projects managed by the company. Key attributes of the projects were also collected, examined, and described in this chapter. Some sensitive project data, such as time and resource (cost) demands or constraints were intentionally transformed to a different unit[1].

Even though there are more than 30 projects executed simultaneously, many of these projects reached high maturity status or are already under series production. Because of this, the case study examines the 5 recently started and active software development projects that are consisting of a total number of 150 activities. It was confirmed that normally there is no logical relationship (i.e., precedence relations) between the individual projects or their activities in the multiproject.

Software projects in the company typically have four main development phases, starting from prototype development (1), to pre-production (2), pre-series production (3), and finally, series (or mass) production (4). In phase (1), basic functions are implemented and put under initial tests. In phase (2), all requested features' logic is realized with basic performance. In phase (3), additional features are tuned for performance for end customers. With phase (4), the parameters are finalized for mass production.

The so-called *features* are requested by customers usually at the beginning of the

[1] A common practice in the literature to keep sensitive information hidden without sacrificing meaningful results.

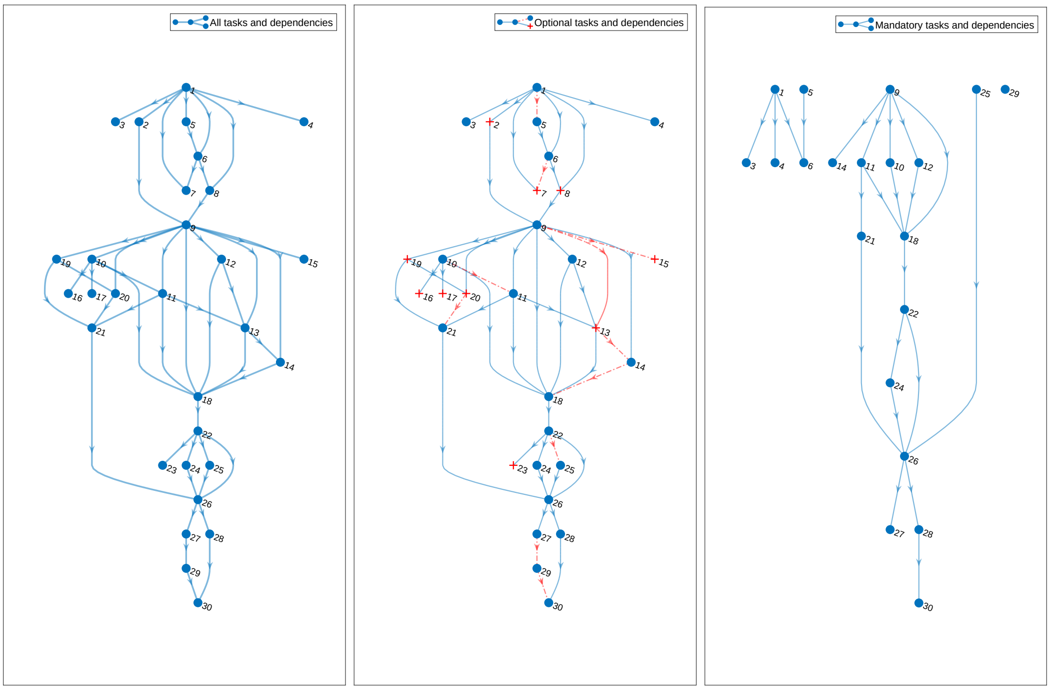
project. Traditional project plans contain all these features, assigned to specific milestones and the plans are established in advance. However, every project has a certain amount of activity that might not need to be realized, some features can change later, e.g., depending on market needs or other sources of constraints. The supplementary tasks (with flexible dependencies) within the sprints can be reordered or postponed, where the realization of features (or part of features) is done. An example of this is testing activities. For an early state, some of the tests executed can be postponed without severe consequences on quality or technical debt, so the priority of doing thorough initial testing is lower. However, with increasing maturity levels, testing gets intense focus and becomes even mandatory when approaching the final software release. Unlike testing, chances of major architectural changes are less likely when software reaches a high maturity. If allowed, dependencies between activities can also be dismissed. Any of these cases can be due to internal or customer decisions, giving management flexibility. These flexible tasks and dependencies were introduced to a new matrix-based flexible project plan. The whole network logic is shown in Figure 34 in Appendix C.

	Project milestone	Activity group	Task	…	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	…
…	…	…	…	…											1							
43	Develop series production SW	Requirements, change requests	Analysis, decision and proposal		1	1	1	1	0.2	0.2	1	1	1	1								
44		Design	Architecture			0.6									1							
45		Implementation	Extended function #1				1	0.1			0.1											
46			Extended function #2					1	0.1													
47			Extended function #3						0.6	0.1												
48			Additional functions							0.8	0.2											
49			Customer function #1								1	0.5	0.3	0.3								
50			Customer function #2									0.5		0.3								
51			Logic performance										1	0.3				1				
52			Parameter performance											1	0.5							
53			Freeze development												1	1					1	
54		Test	Unit tests													0.8	0.8		1			
55			Integration test														0.9	0.9	1			
56			Robustness improvements, bugfixes															1	1			
57			Regression test																0.8	0.5		
58			System and vehicle test																	1	1	
59		Release for series production	System release																		1	1
…	…	…	…																			…

FIGURE 33: Example for a detailed software release
Source: company data

As a detailed example, the milestone *"Develop series production SW"* is shown in Figure 33. In this excerpt, the supplementary tasks and dependencies have a priority lower than 1 (<100%). Considering that the *"Release for series production"* is close, modifying the software architecture has less priority and chance (60%). However, if needed, it strictly depends on the preceding requirements analysis task (100%). Another example is the *"Customer function #2"* task, which has an equal (50%) chance to be realized, skipped or delayed further. The reason could be that it might not be requested, or a previously developed feature can be carried over instead. If it is needed, it has a (50%) priority to make it dependent on the previously developed *"Customer function #1"* task. Regarding testing, a final vehicle test is a must before release, but regression tests are needed in most of the cases (80%).

Figure 34(a) visualizes the structure of a complete single software development project plan. In Figure 34(b) the supplementary tasks and dependencies that can be omitted are highlighted, however, additional dependencies might also be deleted by



(a) All tasks and dependencies (b) Supplementary tasks and dependencies in red (c) Mandatory tasks and dependencies only

FIGURE 34: Flexible tasks within the logic network

removing supplementary tasks. Figure 34(c) shows the minimal structure when all non-mandatory tasks and dependencies are removed from the network, resulting in the minimal structure.

Table 10 shows the total project time of the previously specified structures applied for the original project plan. As expected, the minimal structure yields the shortest time necessary to finish the project, followed by the maximin structure with a duration of $TPT_{maximin} = 157$, by removing only the flexible dependencies. Minimax becomes slightly shorter by omitting only supplementary activities and their dependencies. Maximal structure demands the execution to be the most serial and thus maximizes the duration, while maximin structure does the opposite by removing all flexible dependencies and making the project more parallel while still keeping all supplementary tasks.

TABLE 10: TPT of flexible single project structures scheduled for earliest start time

Structure	TPT
Minimal	115
Minimax	147
Maximin	157
Maximal	213

Table 11 shows the rates of supplementary to mandatory tasks and dependencies in the empirical project plan. The values indicate that the company has relatively high flexibility to exploit within a project. Several dependencies can be omitted, as some functionalities are not interconnected and can be developed in parallel without technological dependency. It can also be observed from Figure 33, that supplementary tasks are typically located in the development part of the project plan, where decisions are made for the actual features to implement. Near the end of the project, rather the dependencies change. For example, the performance, quality goals or other preconditions may be already reached before the final verification, so the depending activity can be already started based on a tailored verification and not need to wait for the final results.

TABLE 11: Flexibility rates for the SW development project

	Supplementary	Mandatory	Rate
Tasks	10	30	33.33%
Dependencies	11	49	22.45%

Figure 35 shows indicator values for the case study project for maximal, minimax, maximin and minimal project structures. The shown indicators were examined previously for the different databases in detail. This evaluation aims to validate some of the assumptions and observations reported in Chapter 4. Looking at the values of TPT in Table 10, it is visible that the maximin structure has a higher TPT compared to the minimax structure. This suggests that the supplementary tasks (with their dependencies) have a higher impact on the project duration than the flexible dependencies, which can be explained by looking at the differences in ratios in Table 11 again. The structural complexity (C) decreases as parallelization increases (I_2). Complexity becomes the lowest with minimal structure. $DMND$ is equal for minimax and minimal structures, and maximal and maximin structures, since this indicator does not take scheduling into account and only depends on tasks and resource values based on tasks. Interestingly, the obstruction factor (OFACT) for resources is close in the maximin and minimax structures, because scheduling is considered in this case. Looking at $NARLF'$ it becomes visible that resource demands get more and more front-loaded with increasing flexibility of maximal to minimal structures. As the value is close to zero in the maximal (original) structure, it can be concluded that the company plan has an initially good balance of resources that can be pulled ahead in the first half of the project by exploiting flexibility. Regarding slack times, the initially low slack time ratios (maximal structure) can be increased either with minimal or maximin structures. While minimal structure results in the highest average slack ratio (XSLACK_R), maximin provides the highest total slack ratio (TOTSLACK_R).

Sensitivity analysis of project plans Using sensitivity analysis, not only the possible range but also the distribution of total project times (TPT) can be analyzed for

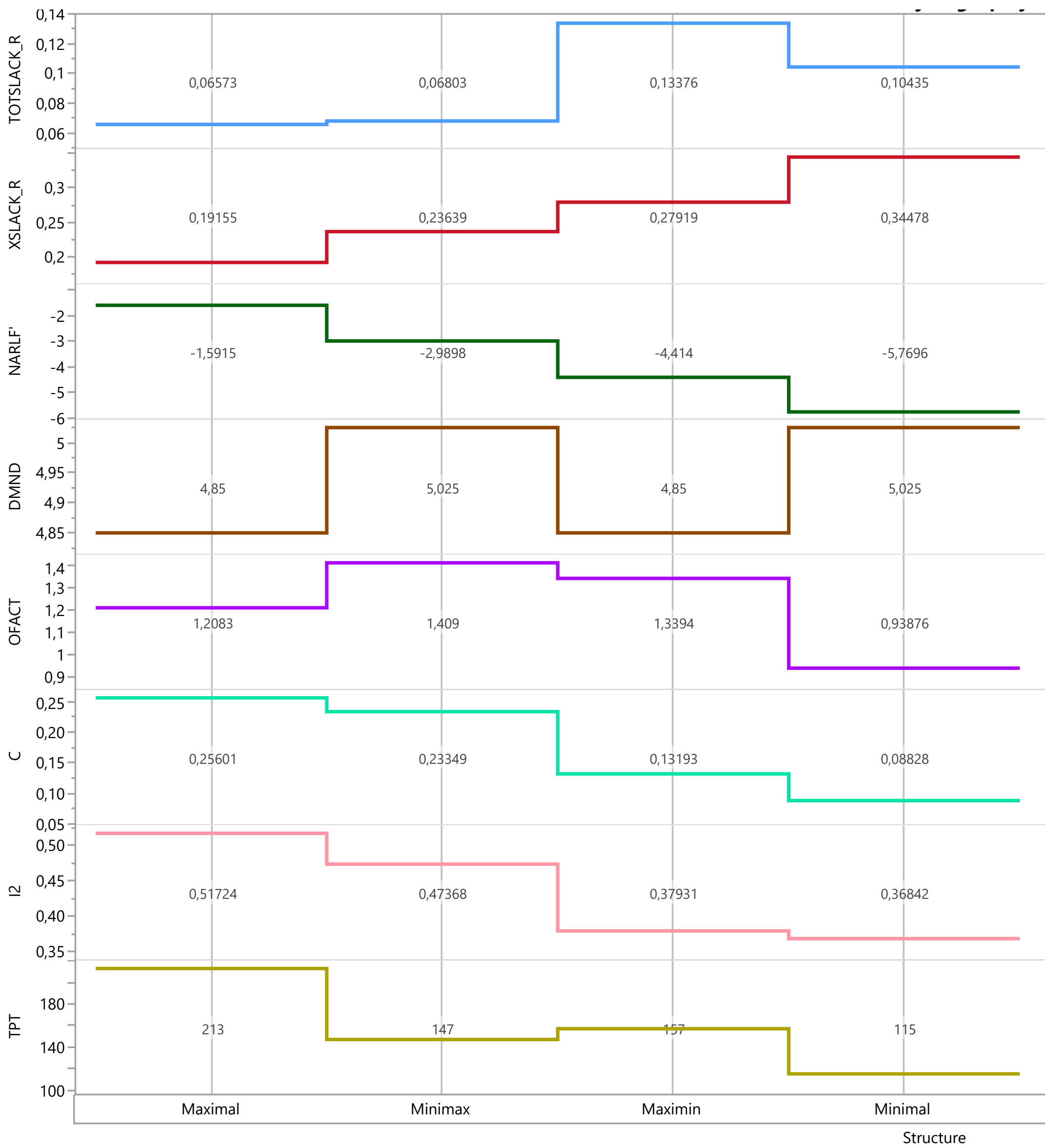


FIGURE 35: Various indicators of flexible project structures in case study
Source: company data

numerous flexibility variations (project scenarios). It is also possible to measure the contribution of the supplementary tasks and flexible dependencies to the variance of TPT. To do this, a Monte Carlo simulation experiment was conducted, which uses random sampling to simulate how changes in supplementary tasks and flexible dependencies impact the total project time. During the simulation, the set of supplementary tasks and flexible dependencies were included or excluded in the original project plan based on their probability (priority)[2] for 100.000 trial runs. Figure 37 shows the observed values of $f\%$ and $s\%$ during the experiment. The simulation results are shown in Figure 36. Using this approach, the contribution to the variance

[2]An arbitrary statistical distribution could also be used to include or exclude flexible tasks and dependencies, e.g., based on expert input

of the multiproject's average TPT was also examined and shown in Figure 51 of Appendix E. Similar results could be observed for the single and multiproject; almost the same tasks are responsible for the changes in the average project durations. For multiproject, the dependency of failsafe functions on requirements and architecture is not as important as for single projects, while the configuration and setup during the design phase have a higher contribution to TPT. In general, the identified activities need heightened focus. Looking at the duration of the whole portfolio of projects reveals that the last subproject's flexible tasks and dependencies have the most impact on the result, as shown in Figure 52 in Appendix E.

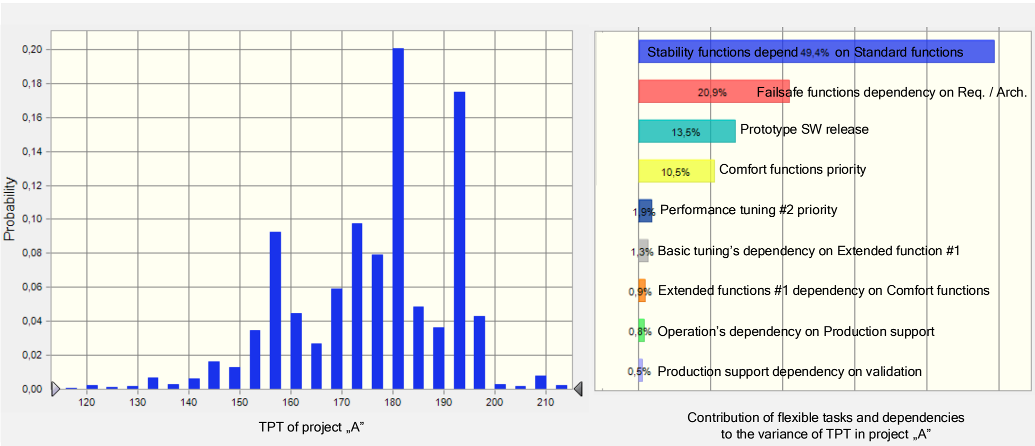


FIGURE 36: Statistical distribution of TPT when flexible tasks and dependencies are varied (left)
Top contributors to the variance of TPT from all flexible tasks and dependencies within the company project (right)

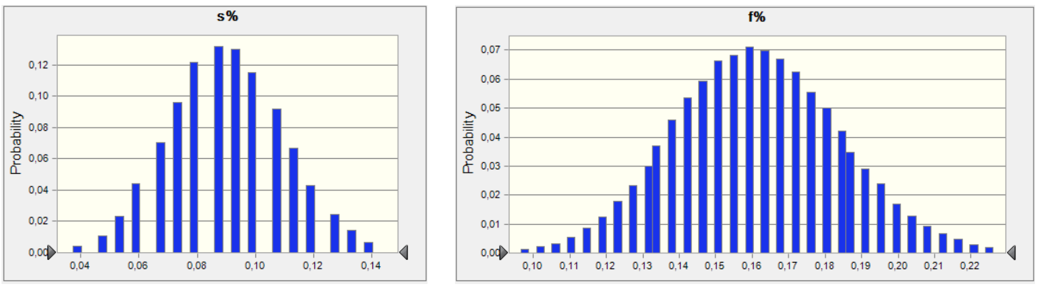


FIGURE 37: Probability distribution of the flexibility indicator values $f\%$ and $s\%$ throughout the sensitivity analysis for the company's multiproject

Finally, using the flexible structure variants, it is possible to examine also the characteristics of multiple projects. The 5 software development (sub)projects have no logical (structural) dependencies with each other. Management makes sure not to start multiple projects at the very same time, to avoid obvious (overlapping) resource peaks. Thus the project arrival times[3] (the earliest time the project can start its main

[3]Release date has the same meaning in the literature but to avoid confusion with software releases, it is intentionally not used here.

activities) are set to 0, 50, 100, 150, and 200, respectively, which means that project "C" can begin 100 time units later than project "A" can.

As mentioned by Pellerin, Perrier, and Berthaut (2020), to this day, exact methods can handle problems typically up to 60 activities and without high resource constrainedness. As the studied multiproject has a high number of activities, heuristics are preferred also because good solutions must often be determined quickly in practice. To provide the best trade-off between accuracy and computation speed, this study proposes a metaheuristic genetic algorithm to solve these instances to near-optimality. The classical objective of the RCPSP or RCMPSP is to minimize the project duration (makespan) but other (often composite) objective functions can be chosen.

Two global renewable resource types[4] ($\rho = 2$) are used: software developers, and testers. The company has 55 units of developers ($\alpha_1 = 55$) and 45 units of testers ($\alpha_2 = 45$), and as there is no overtime considered, this resource constraint cannot be violated at any time. The chosen objective function was to minimize the average total project time ($\overline{TPT}$) of the multiproject.

After the optimization procedure for 100.000 iterations on each instance, the results show that feasible solutions can be found for all the fixed structures, respecting all constraints, such as resource and time limits given by the company. As the optimization method is not exact, multiple suboptimal solutions are possible, and with other initial values, further tuning of the parameters could produce a better solution, but after evaluation, it was found to be unnecessary in this case.

TABLE 12: Results for scheduling possible structures of the software development multiproject

Structure	Projects	Tasks	Dependencies	Res. constraints α_1, α_2	$\overline{TPT}_{EST}$	$\overline{TPT}_{OPT}$	$TPT_{EST}^{portfolio}$	$TPT_{OPT}^{portfolio}$
Maximal	5	150	49	55; 45	213	214*	413	413*
Maximin	5	150	38	55; 45	157	203*	357	390*
Minimax	5	100	28	55; 45	147	161*	347	361*
Minimal	5	100	22	55; 45	115	147*	315	338*

Note: **resource-feasible solution*

From the summarized results in Table 12, it is visible that all of the earliest start schedules, i.e., all resource-unconstrained cases[5] are infeasible because they violate the resource constraints. The maximal (original) multiproject plan can be finished in 413 time units only after finding a resource-feasible solution by rescheduling activities and causing an increase in the average total project time of the multiproject.

For the maximin and minimax structures, the company needs to invest even more time in the projects to resolve their resource conflicts. Considering flexibility, the optimized maximin structure reduces the average multiproject duration with 5.14%, the minimax reduces approximately 24.77% and a 31.31% reduction can be achieved using the minimal structures.

[4]The simulation model can also handle local resources if the problem requires it.
[5]Also known as the critical path method (CPM) proposed by Kelley Jr and Walker (1959)

The approach and results presented here prove the assumption of optimizing fixed project plans that are generated from flexible ones, providing backward compatibility with the most recent algorithms, traditional approaches, and the relatively few methods that support flexible project plans. The solution is given with the scheduled start times (SST) vector for each activity in the multiproject. For reproducibility, the solution for each structure is given in Appendix F in Table 23, and Figure 53 shows an example for the multiproject and project resource profile graphs, compared with the earliest schedule times (EST) for the solution of the maximin structure as well.

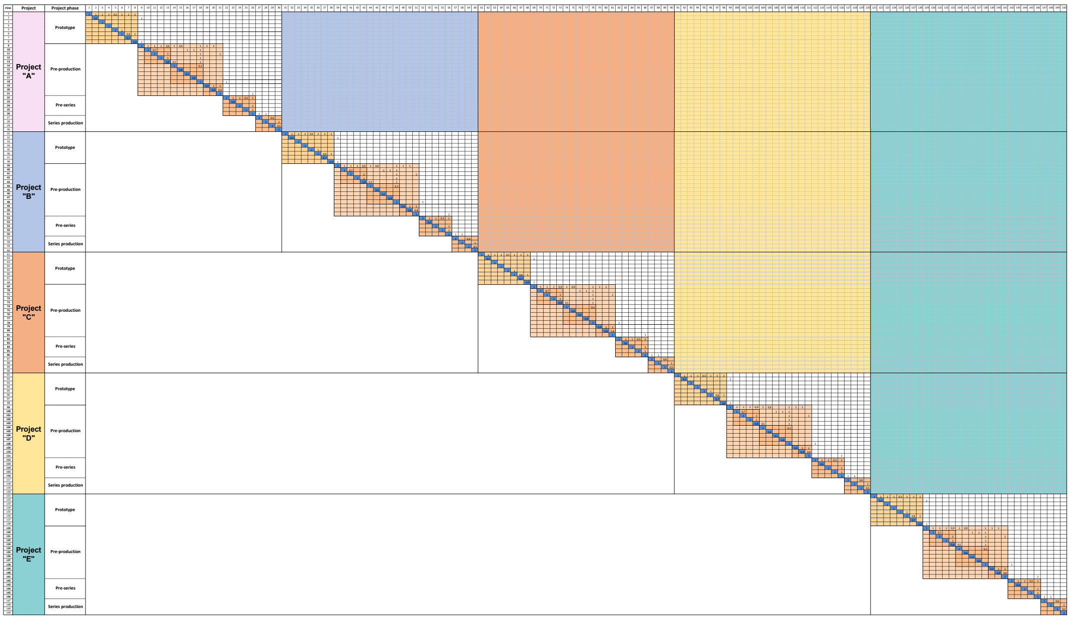


FIGURE 38: Overview of the company multiproject plan

6.1.4 Implications

The case study provided valuable insight into the previously observed phenomena in a real-life context. The analysis results were discussed with the relevant experts in the organization to validate its correctness, gather feedback and minimize mistakes or psychological biases. The parameter values observed from company plans validate the defined ranges used throughout the simulation process and are coherent with the empirical observations during data collection. One of the main findings of the case study is that the relatively high available flexibility ratios are not directly considered by the company, at least not on the planning level. With the help of the proposed simulation and optimization framework, it is possible to better utilize flexibility and improve the company's (re)planning processes. Table 24 in Appendix F shows the details of how the proposed toolchain can be applied in practice.

6.2 Threats to validity

The effect of threats to validity needs to be carefully considered not only in the outcome of the research but also during research. Validity is a goal, that cannot be assured, but following a defined structure from the literature, i.e., conclusion-, internal-, construct-, and external validity (Wohlin et al., 2012), threats can be identified and addressed as a mitigation strategy. The validity analysis will be discussed in detail in the following section.

Conclusion validity: besides statistical significance, the necessary assumptions were checked for the statistical methods used in the research (e.g., sample size, independence, normality, homogeneity of variances, etc.). For the metaheuristic optimizations and stochastic simulations (e.g., sensitivity analysis), the number of iterations was defined and set according to typical values from the literature considering the number of input parameters and combinations. Model variables and effects were also analyzed ceteris paribus, changing one at a time while others held constant. The checked ranges included extremely high and low values for each parameter. In stochastic simulations, descriptive statistics were used to show the central tendency and dispersion of results from multiple runs, instead of comparing them to single values. Random numbers were generated based on an initial pseudo-random seed for comparability and reproducibility.

Internal validity: The structural flexibility of tasks and dependencies was generated based on uniform random distribution to avoid any modifying effects of a specific statistical distribution and unnecessary bias in interpreting the outcome of the simulation runs. Furthermore, the number of iterations and sample size were set according to the previously checked stochastic variability of the model. The simulation model's assumptions were peer-reviewed by experts from the field and found no direct impact on the outcome of the independent variable or similar explicit mechanisms implemented.

Construct validity: Simulation is a widely accepted and applicable method in the literature for the topics addressed in this dissertation. Several real-life databases are applied within the research to compare real parameter settings with several artificial ones from the literature. The controlled parameters' effects were visible and could be verified on implemented charts (e.g. detailed resource profiles) and data visualizations within the proposed simulation software. Interactive debugging was used to see the whole chain of effects within the model execution (e.g., spreadsheet trace dependents feature, set breakpoints, etc.). Formulas were checked to produce the correct output. The whole simulation framework was tested and iteratively reviewed during development. Unit tests were applied to support development, regression testing, and consistency. Calculations were cross-checked with examples or results available in the literature. Both academic and professional reviewers with relevant experience made peer reviews and found no missing real-world variables or relationships between them in the model.

External validity: The possibility to exploit structural flexibility, which has originally emerged from the software development environment, is growing with the application in other industries (Batselier and Vanhoucke, 2015). Furthermore, for single projects, it was possible to include a real-life database from five different industries[6]. However, this option is not available for multiprojects due to a lack of relevant empirical data in the literature. To fill this gap, a case study research was carried out in a real multiproject environment considering software development projects. The distribution of project characteristics, such as project duration was compared to real-life cases. The generalization of results is thus possible for multiple industries and contexts where agile approaches apply to some extent.

[6]The covered industries are: IT, production, construction, education, and events

Chapter 7

Summary and Conclusion

In the current dissertation, a quantitative approach supplemented with a case study was provided to evaluate the effects of flexibility on different indicators and project databases. The aims set at the beginning of this research were successfully reached:

- ✓ To specify a matrix-based method, which can handle
  - [+] single and multi-level projects,
  - [+] multiple execution modes,
  - [+] flexible projects besides traditional ones.
- ✓ To collect existing heterogeneous project databases, including:
  - [+] simulated (artificial),
  - [+] real-life projects.
- ✓ To examine the effects of flexibility not only on the project structure but on the project demands as well.
- ✓ To provide a framework for effective planning of flexible (multi)project plans.

7.1 Research theses

According to the research questions formed in Section 1.2, four research theses were formulated, considering the results of Chapters 4, 5, and 6.

RT1: [Model] The proposed unified matrix-based project-planning model (UMP) can represent both traditional and flexible single project, multiproject, and program plans. It addresses the demands of renewable and non-renewable resources, time, cost, and quality with single and multiple execution modes.

RT2: [Structures] The flexible structure generator (FSG), is able to specify possible minimal, minimax, maximin, and maximal matrix-based structures corresponding to a defined flexibility parameter, which can be added to the model. The planning phase of projects is improved by considering these additional outcomes with their demands.

RT3: [Indicators] There is a relationship between the modeled flexibility and topology, time-, and resource-related indicators.

RT3.1: [Topology] With an increased rate of flexibility, structural indicators show reduced complexity and reduced serial completions (higher parallelity) for minimal structures.

RT3.2: [Time] As the rate of flexibility increases, time-related indicators show decreased project duration and increased average slack ratio.

RT3.3: [Resources] With increased flexibility ratio, resource-related indicators show higher average resource utilization and higher resource constrainedness considering an early schedule.

RT3.4: [Planning] Flexibility has a negative effect on multiproject planning by significantly increasing the variance of average total project times compared to the traditional method where multiproject plans are more predictable.

RT4: [Solution] With the help of the proposed minimal, minimax, maximin, and maximal structures, it is possible to specify multilevel project plans with supplementary tasks and flexible dependencies in a deterministic way, and solve them both with flexible and traditional methods and algorithms. Depending on the considered constraints on time, resources or cost, it is possible to find a feasible, near-optimal solution that minimizes the (multi)project duration or other objective function(s).

The previously formulated research assumptions could be verified with the results that are validated in Chapter 6, with a case study from an automotive company.

To model heterogeneous project databases, a unified matrix-based project-planning model (UMP) is proposed. To combine existing project databases from the literature, a compound matrix-based project database (CMPD) is proposed that can also handle flexibility. In addition, a flexible structure generator (FSG) is proposed to extend existing project databases with specified structures corresponding to the given flexibility parameter. Companies dealing with agile planning considering supplementary (prioritized) activities and dependencies in a project often make decisions and estimates based solely on previous experience. The defined structures can enhance the planning of projects by considering their attributes and demands as well. Traditional algorithms can also be tested in flexible project management environments by providing new combinations of the structural- and demand-related indicator values.

As Table 13 highlights the applicability of the proposed models and methods, the proposed UMP addresses both individual and multiple projects, single and multimodal completions, renewable and nonrenewable resources, cost and quality parameters, traditional and flexible project plans (see Table 13). The unified database contains both artificial (simulated) and real-life data sources. The offered parsers are prepared for single and multimode completion modes as well. However, to the author's best knowledge, there is no existing real-life database for multi-projects and multimodal completion modes. Therefore, the proposed model and methods cannot be tested in these types of real-life projects. The proposed CMPD provides a wider range of values to test project schedules and resource allocation algorithms by introducing flexibility. These parsers, generators, and indicators are available at `https://github.com/novakge/project-parsers` and `https://github.com/novakge/project-indicators`. Table 14 shows the summary of the research.

TABLE 13: Summary table of employed models, generators and databases, and limitations

Data	Type of	Comletion	UMP		CMPD		FSG	Analyzed?	
source	projects	modes	Traditional	Flexible	Traditional	Flexible		Traditional	Flexible
Simulated	Single project	Single-mode	X	X	X	X	X	X	X
Simulated	Single project	Multi-mode	X	X	X	X	X	X	X
Simulated	Multi-project	Single-mode	X	X	X	X	X	X	X
Simulated	Multi-project	Multi-mode	X	X	-	-	-	-	-
Real-life	Single project	Single-mode	X	X	X	X	X	X	X
Real-life	Single project	Multi-mode	-	-	-	-	-	-	-
Real-life	Multi-project	Single-mode	?	?	-	-	-	?	?
Real-life	Multi-project	Multi-mode	-	-	-	-	-	-	-

Notations: 'X' addressed, '-' not addressed, '?' partially addressed.

7.2 Contribution to literature

No databases are currently available to help design and schedule (structurally) flexible projects. There is a lack of project related indicators that characterize flexible project plans. This research helps fill these gaps. The contributions to the literature are summarized below.

1. A unified matrix-based project-planning model (UMP) is proposed to unify a set of heterogeneous single- and multiproject databases into a compound matrix-based project database (CMPD).

2. The proposed CMPD is complemented by the ability to model flexible dependencies and completion priorities.

3. Minimal, minimax, maximin, and maximal structures are generated to specify the minimal and maximal demands with the proposed flexible structure generator (FSG).

4. Structure-related, time-related, and resource-related indicators are modified to address the flexible nature of projects.

10 single project databases, including 22 datasets from sources including Patterson, SMCP and SMFF, PSPLIB, RG300 and RG30, Boctor, MMLIB, MMLIB+, and a real-life project database were collected, processed, and combined into a matrix-based project library, together with 5 multiproject databases, such as BY, RCMPSPLIB, MPSPLIB, MPLIB1 and MPLIB2 including 10 datasets.

Current research shows a way of extending the databases to address the flexible nature of the projects. It gives flexibility-dependent versions of the complexity and the time-related and resource-related indicators of individual projects that can also be applied to multiprojects.

It provides valuable insights into different database characteristics through adapted indicators and examines the effects of flexibility on project structure and demands including the effect on multiple modes in single projects.

7.3 Practical implications

The proposed matrix-based model addresses time, cost, renewable and non-renewable resource demands, quality parameters and considers multiple completion modes for multilevel projects. The proposed method does not only unify the heterogeneous databases but also helps users to develop, evaluate and compare both traditional and flexible project scheduling algorithms. It extends databases with a wider range of indicator values to test and provides a bridge between traditional and flexible approaches using the defined structures.

As part of the research, the developed parser tool was extended with reconstructed database formats, that had been either missing from or inadequately documented in the existing literature. The newly introduced and adapted indicators can be used to evaluate and compare various project plans of specific scenarios with the help of the defined structures. Structural, complexity, time, and resource (cost) attributes support the characterization and comparison of multi-level project plans. It is possible to compare values from previous experiences, such as successful projects, or typical values from other industries, e.g., from real-life database(s).

The proposed simulation framework provides a quantitative foundation for multi-level project planning or replanning and related decisions by considering the effects of a chosen flexible scenario on other projects in the portfolio, for example, taking into account the feasibility, project scope, resources, time, etc. It is capable to find a feasible (near) optimal solution for multi-level problems with respect to various target functions and given constraints, utilizing a metaheuristic optimization engine. The planning process can be further enhanced with the sensitivity analysis of flexible project plans. The simulation tool has an intuitive graphical user interface with various project settings and visualization possibilities, e.g., to compare individual and aggregated resource levels, durations, etc.

The combined database is open to the public and solves the problem of limited data availability. It minimizes common entry barriers (time, effort, and the need for specific knowledge) to further research. The reproduction of the composite database and results are guaranteed (Kosztyán and Novák, 2022a,b), furthermore, maintenance and verification efforts are minimized with the unified format and the provided unit tests[1], which helps control potential contributions from the scientific or

[1]These tests ensure that the tool performs its intended functions correctly, such as parsing input files. They are used to verify changes or updates to the tool, not to introduce new bugs or regressions that break existing functionality

professional community. The research is expected to accelerate the collaboration between researchers and practitioners.

Current research opens up possibilities for future studies also. New indicators could be developed, and the list of existing ones could be extended from the literature. Similarly, new databases and formats can be easily incorporated once available (including flexible ones). Artificial instances could be procedurally generated based on multiple empirical indicator values from real life and from previous project experiences. The indicators can even be used as objective functions for optimizations. The effect of using different statistical distributions for activity and dependency flexibility could be another direction of research. Analyzing project programs within a portfolio is another promising area for future research.

TABLE 14: Research summary

Item	Statement
RQ1:	*How to create a unified model that can represent the heterogeneous project and multiproject databases available in the literature?*
RA1:	A model can be created that unifies the different project and multiproject database formats from the literature, including time, cost, renewable-, nonrenewable-resource and quality demands. Existing databases can be imported and further extended with flexible tasks and dependencies into a single, matrix-based database.
RT1:	[Model] The proposed unified matrix-based project-planning model (UMP) can represent both traditional and flexible single project, multiproject, and program plans. It addresses the demands of renewable and non-renewable resources, time, cost, and quality with single and multiple execution modes.
RQ2:	*How the flexibility of single- and multiproject plans can be modeled?*
RA2:	Flexible project plans can be generated from existing traditional (multi)project plans and new possible structures can be added to the model to improve the planning process.
RT2:	[Structures] The flexible structure generator (FSG), is able to specify possible minimal, minimax, maximin, and maximal matrix-based structures corresponding to a defined flexibility parameter, which can be added to the model. The planning phase of projects is improved by considering these additional outcomes with their demands.
RQ3:	*What characterizes the topology (structure) and the different demands of the flexible project and multiproject plans?*
RA3:	Existing project-related indicators for topology, time- and resource-related demands can be adapted for flexible projects and multiprojects to analyze the effects of flexibility.
RT3:	[Indicators] There is a relationship between the modeled flexibility and topology, time-, and resource-related indicators.
RT3.1:	[Topology] With an increased rate of flexibility, structural indicators show reduced complexity and reduced serial completions (higher parallelity) for minimal structures.
RT3.2:	[Time] As the rate of flexibility increases, time-related indicators show decreased project duration and increased average slack ratio.
RT3.3:	[Resources] With increased flexibility ratio, resource-related indicators show higher average resource utilization and higher resource constrainedness considering an early schedule.
RT3.4:	[Planning] Flexibility has a negative effect on multiproject planning by significantly increasing the variance of average total project times compared to the traditional method where multiproject plans are more predictable.
RQ4:	*How is it possible to find feasible (sub)optimal solutions for the single- and multiproject plans considering flexibility?*
RA4:	Flexible multilevel projects can be scheduled and near-optimal solutions can be found considering constraints. A simulation framework can be constructed to handle flexible dependencies and supplementary tasks.
RT4:	[Solution] With the help of the proposed minimal, minimax, maximin, and maximal structures, it is possible to specify multilevel project plans with supplementary tasks and flexible dependencies in a deterministic way, and solve them both with flexible and traditional methods and algorithms. Depending on the considered constraints on time, resources or cost, it is possible to find a feasible, near-optimal solution that minimizes the (multi)project duration or other objective function(s).

Chapter 8

Limitations

To ensure the comparison between simulated and real-life projects, projects were examined mainly with time and renewable resource demands. However, the presence of nonrenewable resources, cost, and quality demands would open possibilities for further research. Moreover, with the introduction of both artificial and real-life multi-mode multiproject, agile single project, and agile multiproject databases, it would be interesting to compare these with existing databases as well. Currently, there are no real-life multiproject and no agile project databases (of any kind) available, thus the direct comparison between simulated (artificial) and real data is limited to single projects. Multiproject plans from other industries could further diversify the scope of analysis.

Flexibility and uncertainty are two related but distinct concepts in project management. Uncertainty is referred to as having "only partial knowledge of the outcome and the situation" (Meredith et al., 2017). Uncertainty characterizes the unknowns, while risks can have either positive (opportunities) or negative effects (threats) and are usually expressed in terms of impacts of the realization of events or project results, where the probabilities of events can be predicted. Flexibility is referred to the ability to adapt or adjust plans in response to changes or unexpected events. In other words, uncertainty is a source of potential change or disruption, which requires flexibility to be addressed. In this study, structural flexibility is directly considered through changes in scope, i.e., optional tasks and dependencies. Demand-related (time, resource, and cost) flexibilities are only indirectly affected.

Appendix A

Appendix

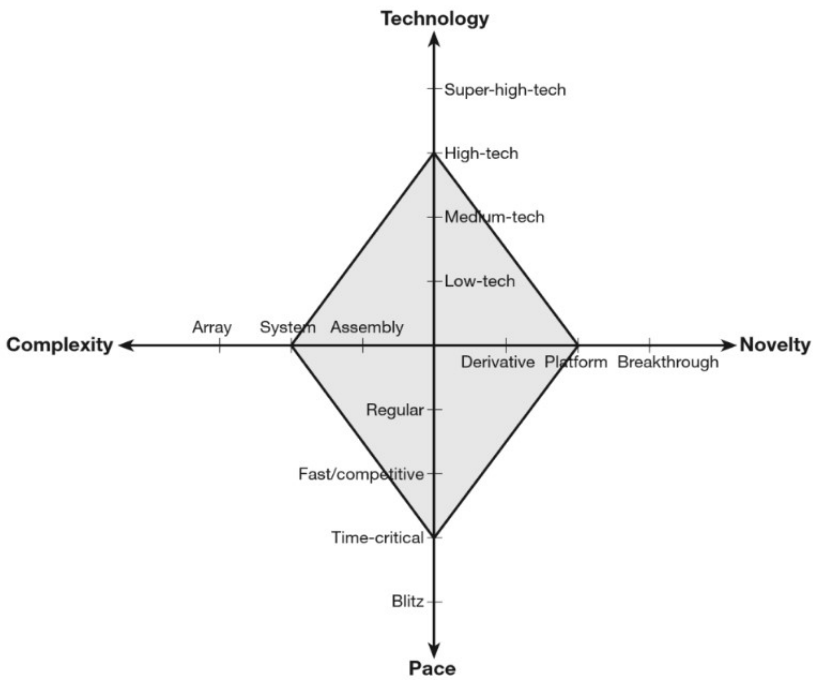


FIGURE 39: Project classification of Shenhar and Dvir (2007)

Appendix B

Further results for indicators: differences, correlation, multiple modes

Note: tables 15-19 contain indicators with significant difference(s). For a given indicator and database, flexibility levels not sharing any letter are significantly different (Piepho, 2018). No comparison is possible between rows (databases), or between the columns (flexibility levels) of multiple indicators.
A higher mean value is assigned with a lower letter in the compact letter display. Kruskal-Wallis non-parametric pairwise comparison method was used with $\alpha = 0.05$ parameter. Fisher's least significant difference (LSD) criterium was used for the posthoc test and Bonferroni correction as an adjustment method.

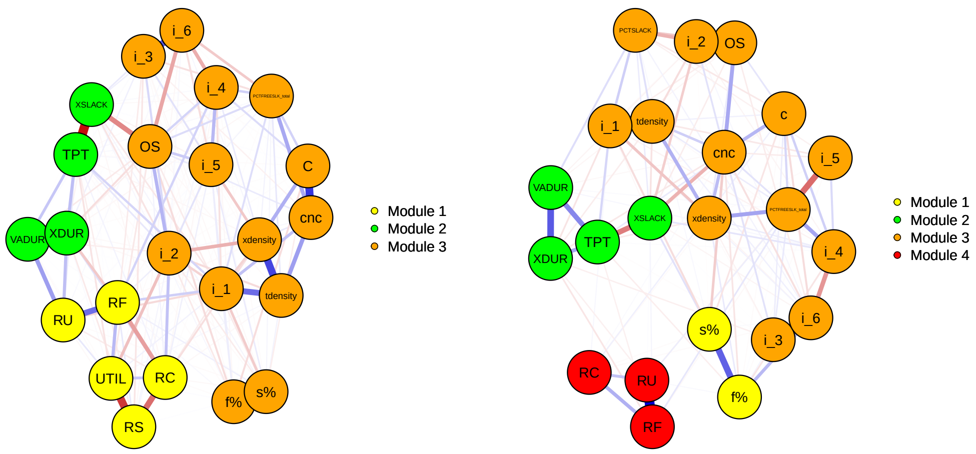
TABLE 15: Differences between structural indicators for flexibility levels in single project databases

	I1					C					OS					CNC					XDENSITY (T-DENSITY)				
	fp=0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4
RG30	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	A (B)	B (C)	C (D)	D (E)
RG300	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
BOCTOR100	A	B	C	D	E	A	B	C	D	D	A	B	C	D	E	A	B	C	D	E	A	A (B)	A (C)	B (D)	C (E)
BOCTOR50	A	B	C	D	E	A	B	C	D	D	A	B	C	D	E	A	B	C	D	E	A	A (B)	A (C)	B (D)	C (D)
J30SM	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
J30MM	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
MMLIB100	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
MMLIB50	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
MMLIBPLUS	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
PATTERSON	A	B	C	D	E	A	B	C	D	D	A	B	C	D	E	A	B	C	D	E	A	A	B	B (C)	C (D)
PROTRACK	A	AB	AB	BC	C	A	B	C	C	C	A	B	C	C	D	A	B	C	D	E	A	A	A (AB)	A (BC)	B (C)
SMCP	A	B	C	D	E	A	B	C	D	D	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
SMFF	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
	I2					I3					I4					I5					I6				
RG30	A	B	C	D	E	B	E	D	C	A	A	B	C	D	E	D	D	C	B	A	E	D	C	B	A
RG300	C	BC	B	A	A	C	BC	B	AB	A	A	A	A	AB	B	A	A	A	A	A	D	CD	BC	AB	A
BOCTOR100	A	B	C	D	E	D	D	C	B	A	A	B	C	D	E	A	B	C	C	C	E	D	C	B	A
BOCTOR50	A	B	C	D	E	C	C	C	B	A	A	B	C	D	E	A	B	C	C	BC	E	D	C	B	A
J30SM	A	B	C	D	E	D	D	C	B	A	A	B	C	D	E	A	B	C	C	B	E	D	C	B	A
J30MM	A	B	C	D	E	E	D	C	B	A	A	B	C	D	E	A	B	C	C	B	E	D	C	B	A
MMLIB100	C	BC	ABC	AB	A	D	CD	C	B	A	A	AB	B	C	D	A	A	A	AB	B	D	CD	C	B	A
MMLIB50	A	A	A	A	A	D	D	C	B	A	A	B	C	D	E	A	A	AB	B	C	E	D	C	B	A
MMLIBPLUS	C	BC	AB	A	A	E	D	C	B	A	A	B	C	D	E	A	A	A	B	C	E	D	C	B	A
PATTERSON	B	A	AB	C	D	D	C	B	AB	A	A	B	C	D	D	A	BC	C	BC	B	D	C	B	B	A
PROTRACK	A	B	BC	CD	D	BC	C	BC	AB	A	A	AB	BC	C	C	B	B	B	AB	A	D	C	B	AB	A
SMCP	A	B	C	D	E	D	D	C	B	A	A	B	BC	CD	D	A	B	B	B	A	E	D	C	B	A
SMFF	A	B	C	D	E	E	D	C	B	A	A	B	C	D	E	A	B	C	C	C	E	D	C	B	A

TABLE 16: Differences between time-related indicators for flexibility levels in single project databases

	TPT					PCTSLACK					XSLACK					TOTSLACK_R				
	fp=0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4
RG30	A	B	C	D	E	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A
RG300	A	A	B	C	D	A	B	C	D	E	D	D	C	B	A	E	D	C	B	A
BOCTOR100	A	B	C	D	E	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A
BOCTOR50	A	B	C	D	E	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A
J30SM	A	B	C	D	E	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A
J30MM	A	B	C	D	E	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A
MMLIB100	A	B	C	D	E	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A
MMLIB50	A	B	C	D	E	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A
MMLIBPLUS	A	B	C	D	E	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A
PATTERSON	A	A	B	C	D	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A
PROTRACK	A	AB	BC	C	C	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A
SMCP	A	B	C	D	E	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A
SMFF	A	B	C	D	E	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A

	XSLACK_R					PCTFREESLK					XFREESLK				
RG30	E	D	C	B	A	A	B	C	D	E	A	B	C	D	E
RG300	C	C	BC	B	A	A	B	C	D	E	A	AB	B	BC	C
BOCTOR100	E	D	C	B	A	A	B	C	D	E	A	A	B	C	D
BOCTOR50	E	D	C	B	A	A	B	C	D	E	A	A	B	C	D
J30SM	E	D	C	B	A	A	B	C	D	E	A	B	C	D	E
J30MM	E	D	C	B	A	A	B	C	D	E	A	B	C	D	E
MMLIB100	D	D	C	B	A	A	B	C	D	E	A	AB	B	C	D
MMLIB50	D	D	C	B	A	A	B	C	D	E	A	A	B	C	D
MMLIBPLUS	E	D	C	B	A	A	B	C	D	E	A	B	C	D	E
PATTERSON	D	C	B	A	A	A	B	C	D	E	A	A	B	C	D
PROTRACK	D	C	B	B	A	A	A	AB	BC	C	A	A	A	B	B
SMCP	E	D	C	B	A	A	B	C	D	E	A	B	C	D	E
SMFF	E	D	C	B	A	A	B	C	D	E	A	B	C	D	E



(a) For the simulated projects

(b) For the real-life database (RS, $UTIL$ cannot be used in correlation graph)

FIGURE 40: Clustered correlation graphs (non-parametric) between the indicators

Note: the correlation strengths are proportional to the tightness of the arcs between the nodes. The blue (red) arcs indicate positive (negative) correlations. Only the significant correlations are represented and nodes are represented only where there is variance. Bonferroni adjustment (Bonferroni, 1936; Hochberg, 1988) was used to address the issue for multiple comparisons for the correlation graph.

TABLE 17: Differences between structural indicators for flexibility levels in multiproject databases

	$\overline{I1}$					$\overline{C}$					$\overline{OS}$					$\overline{CNC}$					$\frac{\overline{XDENSITY}}{(\overline{T-DENSITY})}$				
	fp=0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4
BY	A	B	C	D	E	E	D	C	B	A	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
RCMPSPLIB	A	A	A	A	A	A	AB	BC	C	C	A	AB	BC	CD	D	A	AB	BC	CD	D	A	A (AB)	AB (ABC)	BC (BC)	C
MPSPLIB	A	AB	ABC	BC	C	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
MPLIB1_1	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	A (B)	B (C)	C (D)	D (E)
MPLIB1_2	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	A (B)	B (C)	C (D)	D (E)
MPLIB1_3	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	A (B)	B (C)	C (D)	D (E)
MPLIB2_1	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	A (B)	B (C)	C (D)	D (E)
MPLIB2_2	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
MPLIB2_3	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
MPLIB2_4	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
	$\overline{I2}$					$\overline{I3}$					$\overline{I4}$					$\overline{I5}$					$\overline{I6}$				
BY	D	C	B	A	A	D	C	B	A	A	B	C	E	D	A	E	D	C	B	A	E	D	C	A	B
RCMPSPLIB	A	A	A	A	A	C	BC	ABC	AB	A	A	A	A	A	A	A	A	A	A	A	C	BC	AB	A	A
MPSPLIB	A	B	C	D	E	D	D	C	B	A	A	B	C	D	E	A	B	C	D	D	E	D	C	B	A
MPLIB1_1	A	B	C	D	E	B	D	C	B	A	A	B	C	D	E	A	B	C	D	D	E	D	C	B	A
MPLIB1_2	A	B	C	D	E	C	E	D	B	A	A	B	C	D	E	A	B	C	D	E	E	D	C	B	A
MPLIB1_3	A	B	C	D	E	C	E	D	B	A	A	B	C	D	E	A	B	C	D	E	E	D	C	B	A
MPLIB2_1	A	B	C	D	E	B	E	D	C	A	A	B	C	D	E	A	B	D	E	C	E	D	C	B	A
MPLIB2_2	A	B	C	D	E	B	E	D	C	A	A	B	C	D	E	A	B	D	E	C	E	D	C	B	A
MPLIB2_3	A	B	C	D	E	B	E	D	C	A	A	B	C	D	E	A	B	D	E	C	E	D	C	B	A
MPLIB2_4	A	B	C	D	E	B	E	D	C	A	A	B	C	D	E	A	B	D	E	C	E	D	C	B	A

TABLE 18: Differences between time-related indicators for flexibility levels in multiproject databases

	$\overline{TPT}$					$\overline{PCTSLACK}$					$\overline{XSLACK}$					$\overline{TOTSLACK\_R}$				
	fp=0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4
BY	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
RCMPSPLIB	A	AB	AB	AB	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
MPSPLIB	A	B	C	D	E	E	D	C	B	A	B	A	A	A	B	E	D	C	B	A
MPLIB1_1	A	B	C	D	E	E	D	C	B	A	D	B	A	B	C	E	D	C	B	A
MPLIB1_2	A	B	C	D	E	E	D	C	B	A	E	B	A	C	D	E	D	C	B	A
MPLIB1_3	A	B	C	D	E	E	D	C	B	A	E	B	A	C	D	E	D	C	B	A
MPLIB2_1	A	B	C	D	E	E	D	C	B	A	E	A	B	C	D	E	D	C	B	A
MPLIB2_2	A	B	C	D	E	E	D	C	B	A	D	A	A	B	C	E	D	C	B	A
MPLIB2_3	A	B	C	D	E	E	D	C	B	A	D	A	A	B	C	E	D	C	B	A
MPLIB2_4	A	B	C	D	E	E	D	C	B	A	D	A	A	B	C	E	D	C	B	A
	$\overline{XSLACK\_R}$					$\overline{PCTFREESLK}$					$\overline{XFREESLK}$									
BY	D	B	A	A	C	A	B	C	D	E	A	B	C	D	E					
RCMPSPLIB	B	B	A	A	A	A	A	B	BC	C	A	A	AB	BC	C					
MPSPLIB	E	D	C	B	A	A	B	C	D	E	A	B	C	D	E					
MPLIB1_1	E	D	C	B	A	A	B	C	D	E	B	A	C	D	E					
MPLIB1_2	E	D	C	B	A	A	B	C	D	E	B	A	C	D	E					
MPLIB1_3	E	D	C	B	A	A	B	C	D	E	B	A	C	D	E					
MPLIB2_1	E	D	C	B	A	A	B	C	D	E	A	B	C	D	E					
MPLIB2_2	E	D	C	B	A	A	B	C	D	E	A	B	C	D	E					
MPLIB2_3	E	D	C	B	A	A	B	C	D	E	A	B	C	D	E					
MPLIB2_4	E	D	C	B	A	A	B	C	D	E	A	B	C	D	E					

TABLE 19: Differences between resource-related indicators for flexibility levels in all databases

		RS					UTIL					XCON					OFACT					UFACT				
		fp=0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4	0	0.1	0.2	0.3	0.4
Single	RG30	A	B	C	D	CD	E	D	C	B	A	E	D	C	B	A	D	C	B	A	A	A	B	C	D	D
	RG300	A	A	A	A	A	A	AB	ABC	BC	C	D	CD	BC	AB	A	A	AB	ABC	BC	C	C	BC	BC	AB	A
	BOCTOR100	A	B	C	D	D	E	D	C	B	A	E	D	C	B	A	D	C	B	AB	A	A	B	C	D	D
	BOCTOR50	A	B	C	CD	D	E	D	C	B	A	E	D	C	B	A	C	B	A	A	A	A	B	C	C	C
	J30SM	A	A	AB	B	B	D	CD	BC	AB	A	E	D	C	B	A	B	B	AB	A	A	A	AB	AB	B	B
	J30MM	A	A	B	BC	C	C	C	B	AB	A	E	D	C	B	A	D	CD	BC	AB	A	A	AB	AB	B	AB
	MMLIB100	B	AB	A	A	A	A	AB	ABC	BC	C	D	D	C	B	A	A	AB	AB	B	B	D	CD	BC	AB	A
	MMLIB50	A	A	A	A	A	A	A	A	A	A	E	D	C	B	A	A	A	A	A	A	C	BC	AB	AB	A
	MMLIBPLUS	C	B	A	AB	AB	A	AB	BC	CD	D	E	D	C	B	A	A	B	C	C	C	E	D	C	B	A
	PATTERSON	A	B	C	D	D	C	C	B	A	A	D	D	C	B	A	B	B	A	A	A	ABC	A	AB	BC	C
	PROTRACK	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
	SMCP	A	AB	ABC	BC	C	C	C	B	A	A	E	D	C	B	A	B	AB	AB	A	AB	A	A	AB	B	B
	SMFF	A	A	AB	B	B	D	CD	BC	AB	A	E	D	C	B	A	C	BC	AB	A	A	A	AB	AB	B	B
Multi	BY	D	D	C	B	A	A	B	C	D	E	E	D	C	B	A	A	B	C	D	E	E	D	C	B	A
	RCMPSPLIB	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
	MPSPLIB	A	A	AB	BC	C	A	A	A	A	A	C	C	BC	AB	A	B	B	AB	AB	A	A	A	A	A	A
	MPLIB1_1	A	B	C	D	D	E	D	C	B	A	E	D	C	B	A	E	D	C	B	A	A	B	C	D	D
	MPLIB1_2	A	B	C	D	D	E	D	C	B	A	E	D	C	B	A	E	D	C	B	A	A	B	C	D	E
	MPLIB1_3	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A	E	D	C	B	A	A	B	C	D	E
	MPLIB2_1	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A	D	C	B	A	A	A	B	C	D	E
	MPLIB2_2	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A	E	D	C	B	A	A	B	C	D	E
	MPLIB2_3	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A	D	C	B	A	A	A	B	C	D	E
	MPLIB2_4	A	B	C	D	E	E	D	C	B	A	E	D	C	B	A	D	C	B	AB	A	A	B	C	D	D

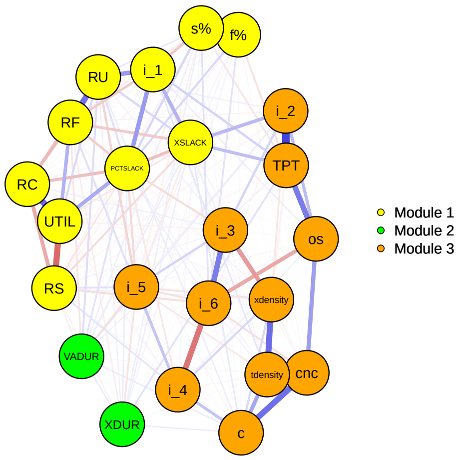


FIGURE 41: Clustered correlation graph (non-parametric) of the multiple project database indicators. Note: indicators represent average values.

FIGURE 42: Single project time-related indicators of multimode datasets

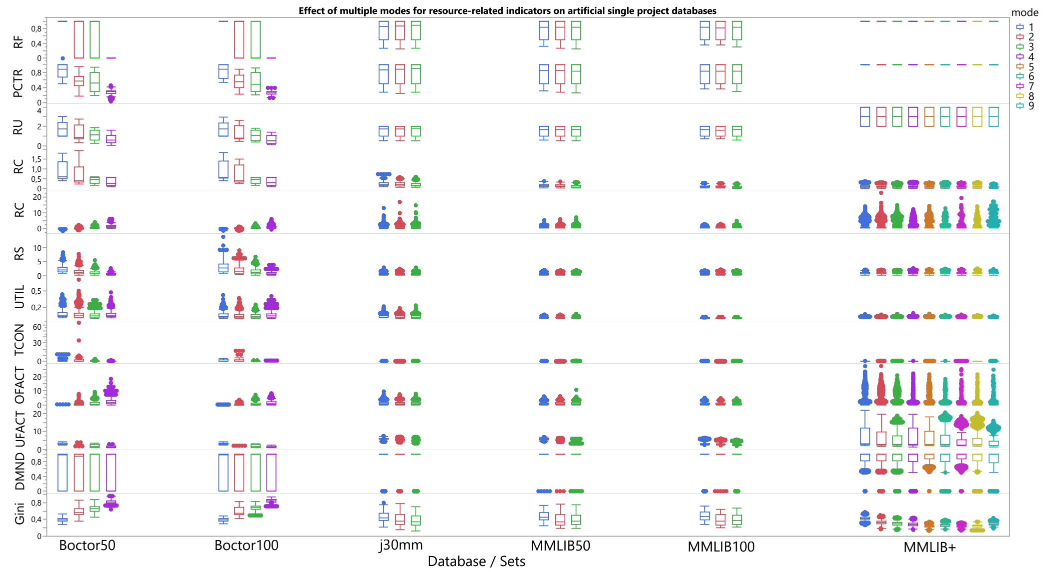


FIGURE 43: Single project resource-related indicators of multimode datasets

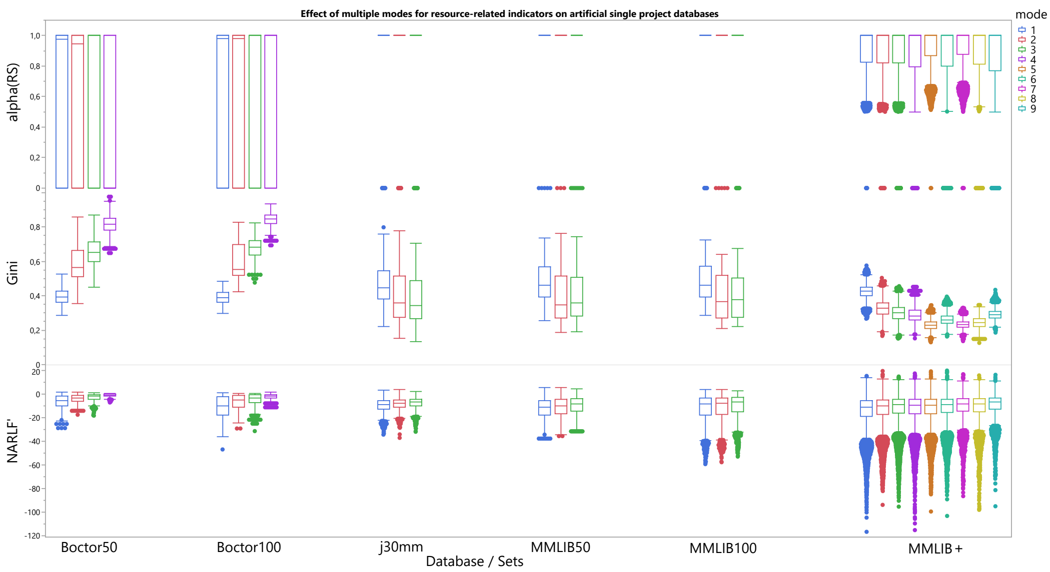


FIGURE 44: Single project distribution of resource-related indicators of multimode datasets

Appendix C

Case study: company project plan with time and resource demands

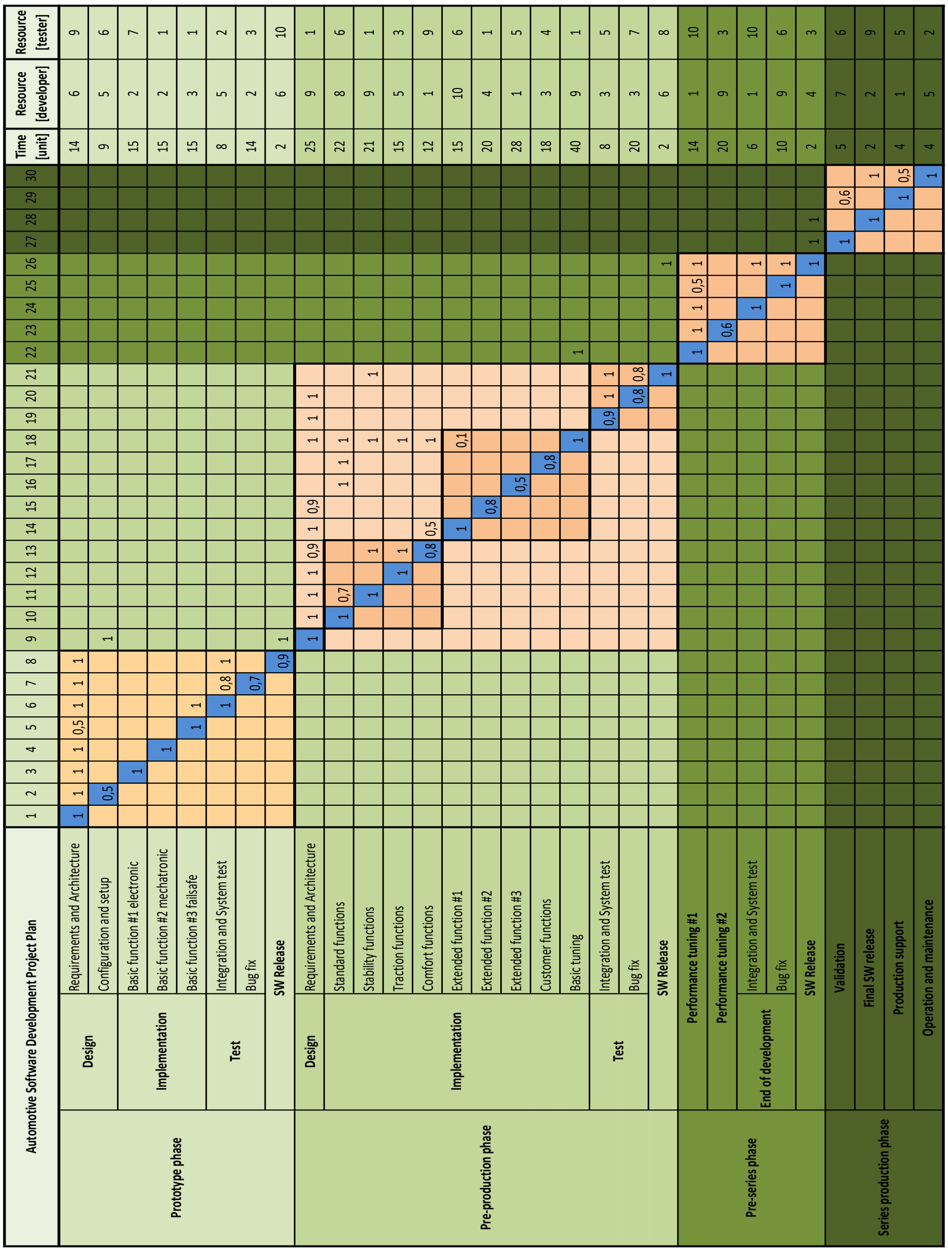


FIGURE 45: Automotive software development project plan

Appendix D

Details of regression for flexibility and duration in multiprojects

A regression model was built to explore further the relationship between flexibility and project duration besides existing descriptive statistics.

The assumptions of linear regression have been verified. The sample size is adequate (Table 7). Linearity can be assumed based on the horizontal character of the residuals vs. the fitted plot. However, normality cannot be assumed based on the histogram (Figure 47), the corresponding statistical tests (e.g., Kolmogorov-Smirnov), or by the Q-Q plot (Figure 48). Outliers are visible on the boxplot, and the residuals vs. leverage plot in Figure 48 shows some influential observations that can affect the regression line. The homogeneity of variances assumption is violated as indicated by the scale-location and spread-level plots on Figure 48-49), and by specific tests (e.g., Levene's test, backed up with a nonparametric Fligner-Killeen's test). This implied that a robust method is necessary. To address the non-normality, a nonparametric test was also used.

For single projects (excluding real-life database), using Spearman's rank correlation method, the relationship between fp and TPT is negative, moderate in strength ($\rho = -0.405$) and statistically significant ($p - value < .001$).

For multiprojects, the same method indicates that the relationship between fp and TPT is negative, moderate in strength ($\rho = -0.573$), and statistically significant ($p - value < .001$).

Using quantile regression ($\tau = 0.5$) the pseudo-R-squared proposed by Koenker (2005) for single projects is $R1 = 0.09$, so the flexibility parameter fp explains approximately 9% of TPT, which is considered a weak effect size ($p - value < .001$). However, for multiprojects, the pseudo-R-squared is $R1 = 0.465$, which can be considered a moderate effect size in the field of this study ($p - value < .001$).

Interpreting the quantile regression results of Table 21, the fp coefficient estimate of -153.83 means that the median (0.5^{th}) quantile of TPT decreases by 153.833 for every one unit increase in fp (independent variable).

To account for the violation of homogeneity of variances, a robust GLS (generalized least squares) regression method was also applied that takes residual weight into account. As fp can take zero value, a $\log(0)$ inverse hyperbolic sine (IHS) transformation was used to avoid issues with the infamous $\log(x+1)$ transformation practices (see, e.g., MaCurdy and Pencavel, 1986).

The resulting adjusted $R^2 = 0.396$, with details shown in Table 22. In addition, Figure 46 shows the linear model only for reference (assumptions violated), together with the visually similar quantile and GLS regression line. The model is statistically significant ($p - value < .001$).

All data, additional tests, figures, calculation details, and results can be found in the supplementary electronic materials listed in Appendix G.

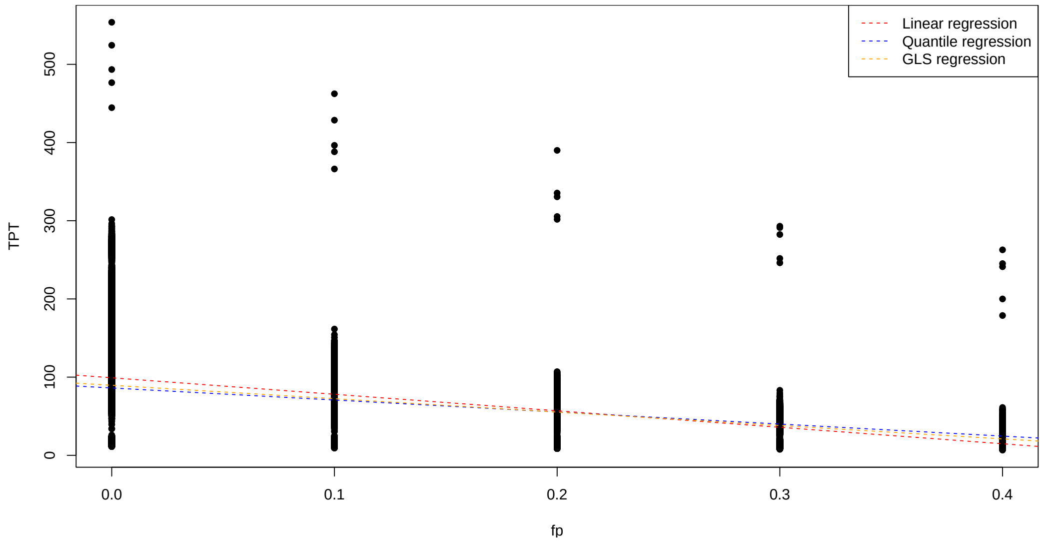


FIGURE 46: Multiproject regressions: effect of flexibility parameter on TPT

TABLE 20: Comparing different quantile regressions for $\tau = \{0.25, 0.5, 0.75\}$

	Dependent variable:		
	TPT		
	(1)	(2)	(3)
fp	-77.500^{***}	-153.833^{***}	-235.750^{***}
	(1.286)	(0.398)	(0.629)
Constant	53.050^{***}	86.150^{***}	121.600^{***}
	(0.502)	(0.154)	(0.238)
Observations	260,690	260,690	260,690
Note:			*p<0.1; **p<0.05; ***p<0.01

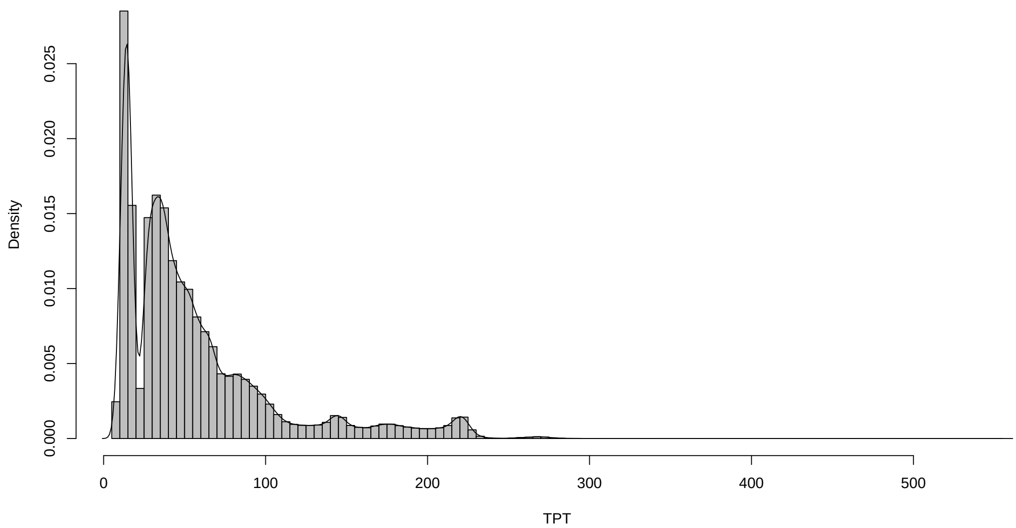


FIGURE 47: Histogram of TPT

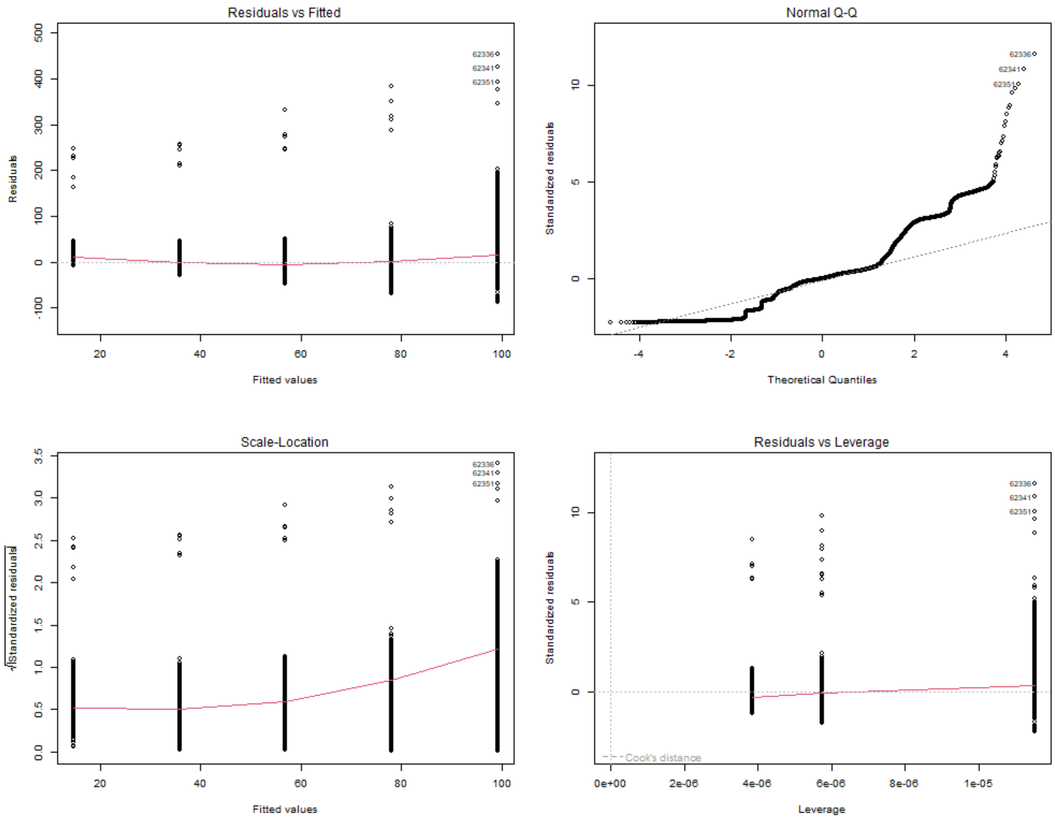


FIGURE 48: Various diagnostic plots for regression

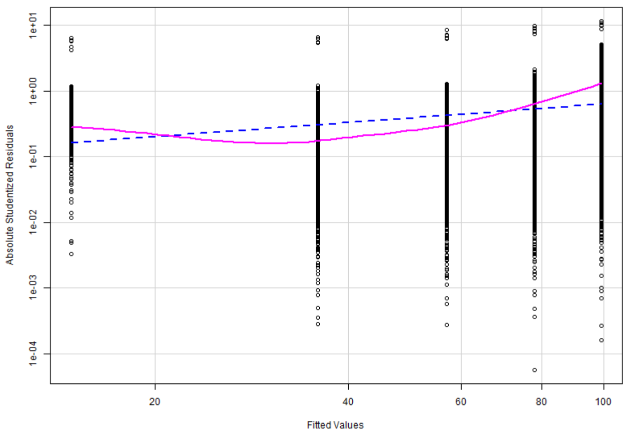


FIGURE 49: Spread-Level plot for regression

TABLE 21: Effect of flexibility on TPT in multiprojects (quantile regression)

	Dependent variable:
	TPT
fp	-153.833^{***}
	(0.398)
Constant	86.150^{***}
	(0.154)
Observations	260,690
Note:	*p<0.1; **p<0.05; ***p<0.01

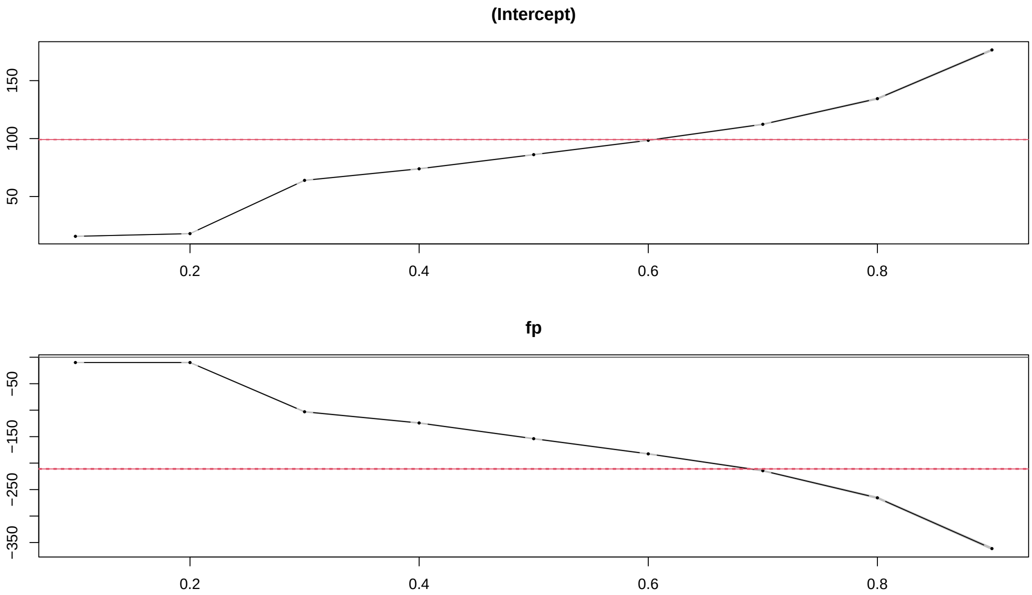


FIGURE 50: Multiple τ test for multiprojects, exploring conditional quantiles other than median

TABLE 22: Effect of flexibility on TPT in multiprojects (GLS regression)

	Dependent variable:
	TPT
fp	-171.399^{***}
	(0.414)
Constant	89.587^{***}
	(0.127)
Observations	260,690
R^2	0.396
Adjusted R^2	0.396
Residual Std. Error	8.030 (df = 260688)
F Statistic	$171{,}065.600^{***}$ (df = 1; 260688)
Note:	*p<0.1; **p<0.05; ***p<0.01

Appendix E

Sensitivity analysis of the company's multiproject

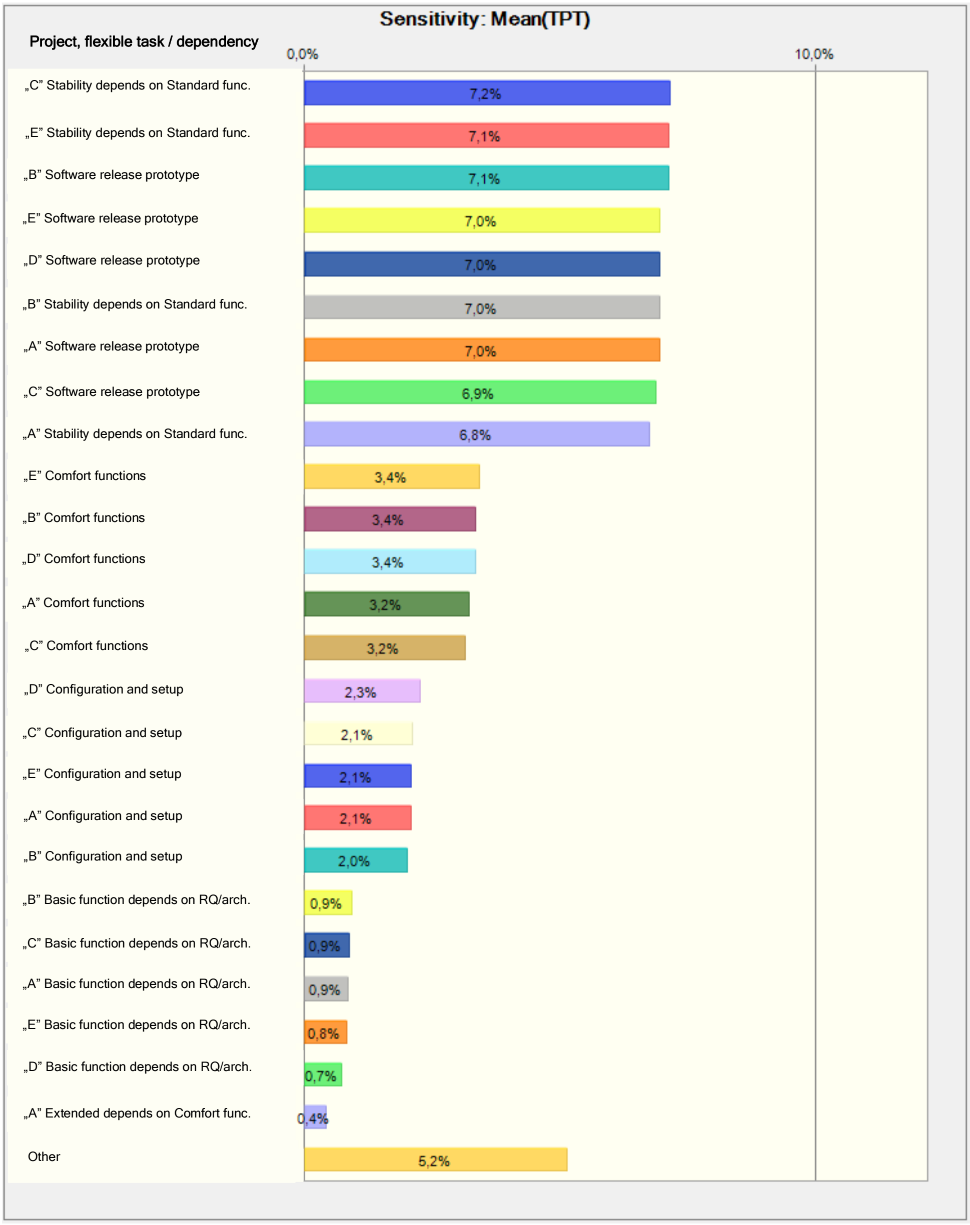


FIGURE 51: The contribution of flexible dependencies and tasks to the average duration of the company's multiproject

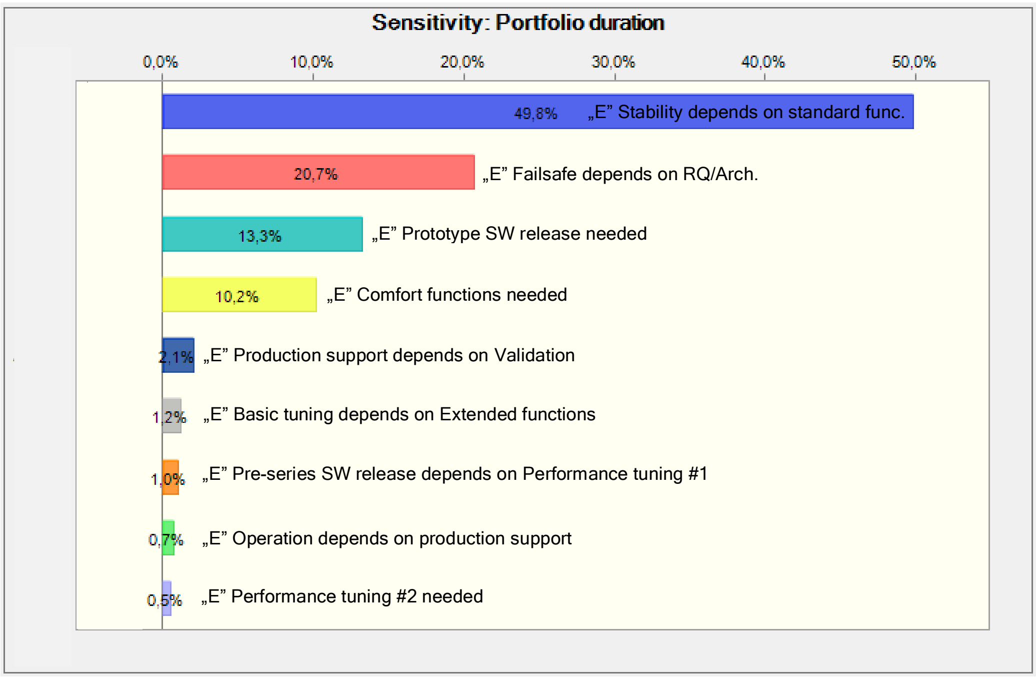


FIGURE 52: The contribution of flexible dependencies and tasks to the duration of the company's portfolio

Appendix F

Solutions of company multiproject plans

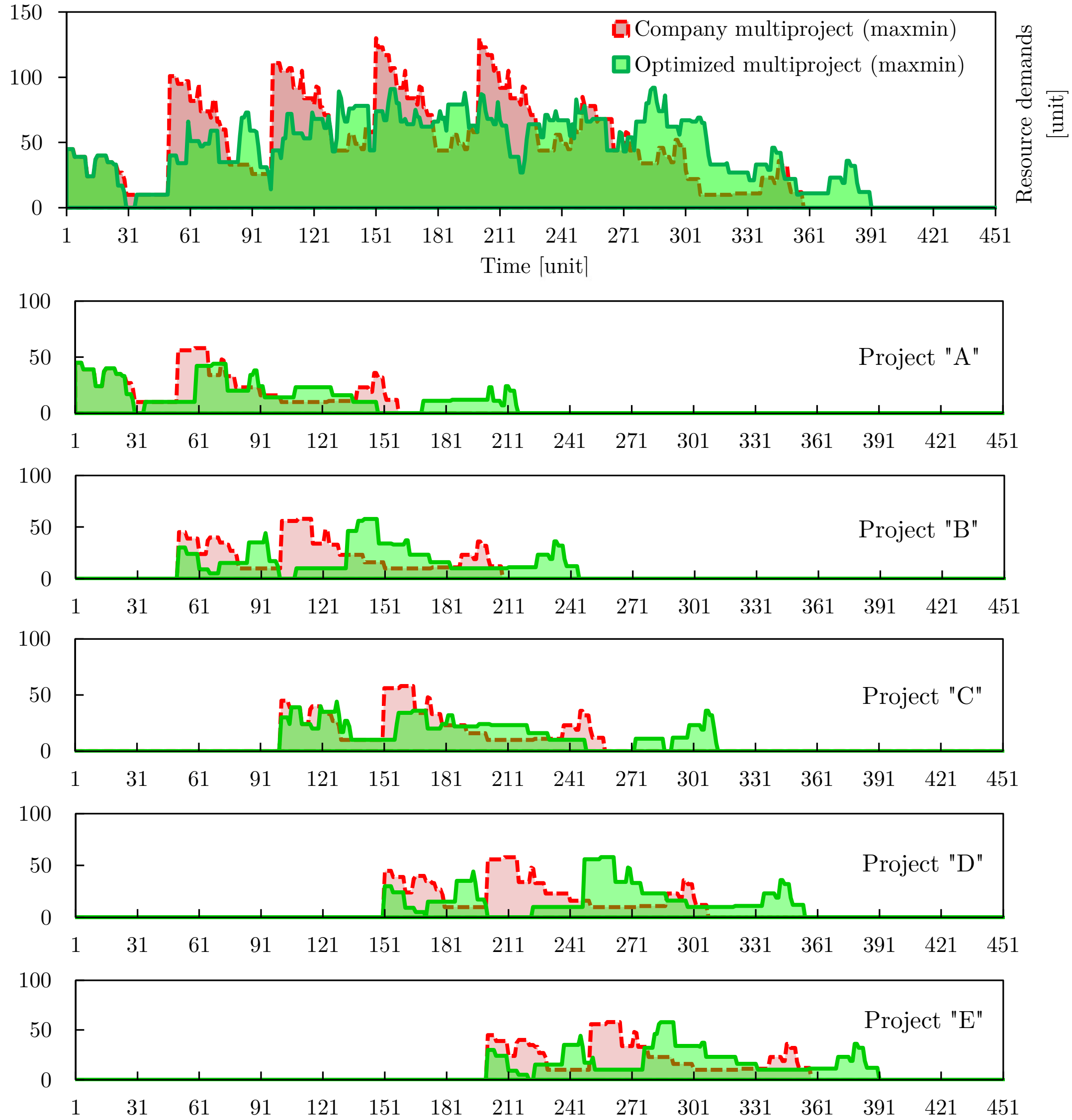


FIGURE 53: Aggregated resource profiles before and after optimization of the maximin company multiproject plan

TABLE 23: Optimized solutions for the different flexible multiproject structures

Structure	$SST_{maximal}$					$SST_{maximin}$					$SST_{minimax}$					$SST_{minimal}$				
Task of subproject	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
T1	0	50	100	150	200	0	70	105	171	223	0	50	100	150	200	0	50	100	150	200
T2	14	64	114	164	214	14	84	119	185	237	14	64	114	164	214	14	64	114	164	214
T3	14	64	114	164	214	14	84	119	185	237	14	64	114	164	214	14	64	114	164	214
T4	14	64	114	164	214	14	84	119	185	237	14	64	114	164	214	14	64	114	164	214
T5	14	64	114	164	214	0	50	100	150	200	14	64	114	164	214	0	50	110	158	209
T6	29	79	129	179	229	15	84	119	185	237	29	79	129	179	229	15	65	125	173	224
T7	37	87	137	187	237	14	84	119	185	237	56	106	156	207	253	23	73	133	181	232
T8	37	87	137	187	237	23	92	127	193	245	66	116	166	216	256	23	73	133	181	232
T9	39	89	139	189	239	34	107	131	222	251	14	64	114	164	214	13	64	113	163	211
T10	64	114	164	214	264	85	132	180	247	281	39	89	139	189	239	38	89	138	188	236
T11	86	136	186	236	286	59	137	157	247	283	61	111	161	211	261	61	110	161	208	249
T12	93	114	164	214	264	59	132	181	247	276	39	89	139	189	239	38	89	138	188	236
T13	108	157	207	257	307	80	158	196	268	304	54	104	154	204	254	53	104	153	203	251
T14	120	169	219	269	319	59	132	156	247	276	39	89	139	189	239	38	89	138	188	236
T15	64	114	164	214	264	0	50	100	150	200	54	104	154	204	254	53	104	153	203	251
T16	86	136	186	236	286	107	154	202	269	303	54	104	154	204	254	53	104	153	203	251
T17	86	136	186	236	286	107	154	202	269	303	54	104	154	204	254	53	104	153	203	251
T18	135	184	234	284	334	107	170	208	280	316	82	132	182	232	282	82	131	182	229	270
T19	64	114	164	214	264	59	132	156	247	276	122	172	222	272	322	122	171	222	269	310
T20	72	122	172	222	272	67	140	164	255	284	122	172	222	272	322	122	171	222	269	310
T21	107	157	207	257	307	87	160	178	268	304	82	132	182	232	282	82	131	182	229	270
T22	175	224	274	324	374	169	210	272	320	356	122	172	222	272	322	122	171	222	269	310
T23	189	238	288	338	388	183	224	290	334	370	136	186	236	286	336	136	185	236	283	324
T24	189	238	288	338	388	201	224	298	334	370	136	186	236	286	336	136	185	236	283	324
T25	189	240	288	338	388	0	50	100	150	200	136	186	236	286	336	0	54	100	271	254
T26	199	250	298	348	398	207	230	304	340	376	146	196	246	296	346	142	191	242	289	330
T27	201	252	300	350	400	209	232	306	342	378	148	198	248	298	348	144	193	244	291	332
T28	201	252	300	350	400	209	232	306	342	378	148	198	248	298	348	144	193	244	291	332
T29	206	257	305	355	405	0	50	100	150	200	153	203	253	303	353	0	50	100	150	200
T30	210	261	309	359	409	211	234	308	344	380	157	207	257	307	357	146	195	246	293	334

TABLE 24: Practical guide using the toolchain presented in this study

When (step)	What (task)	Why (goal)	Which (tool)	How (usage)	Example (input/output)
1.)	Import or create plans	Read existing (traditional) project plans	Parser (MATLAB)	Run 'save_all' to process all datasets	Input: ./data/<dataset> Output: ./data/<dataset>_output/<instance_name>.MAT
		Create/adapt traditional project plan	MATLAB (editor)	Modify plan, or use the matrix-based template	Input: Project_template_traditional.MAT Output: <project_name>.MAT
		Create/adapt flexible project plan	MATLAB (editor)	Modify plan, or use the matrix-based template	Input: Project_template_flexible.MAT Output: <project_name>.MAT
2.)	Incorporate flexibility	Generate structure variants {maximal, maxmin minmax, minimal}	Traditional: FSG (indicators_all); Flexible: FSG (flex2struct)	Run 'indicators_all' for all traditional instances; Run 'flex2struct' for existing flexible plan	Input: ./data/<instance_name>.MAT (Instances: ./out/<project_name>_ff*_mode*.mat)
3.)	Calculate indicators	Calculate indicator values for all structures Compare different structures	FSG (indicators_all); (arbitrary spreadsheet or statistical SW)	Check results of 'indicators_all'	Output: results_<date>.csv
4.)	Optimize plans	Optimize project plans considering objective(s) and constraints	PEM_simulation (excel) (or arbitrary RCPSP solver)	Import PDM to spreadsheet; Set constraints, objective function(s), trials, etc; Run OptQuest™ optimization.	Input: Project Domain Matrix Output: Optimized activity schedule (SST)
5.)	Analyze sensitivity	Check sensitivity of project plans	PEM_simulation (excel)	Select tasks and dependencies to vary and their probability distribution(s). Run simulation.	Input: flexible plan imported to PEM_simulation.xls Output: results of sensitivity analysis (statistics, charts)
6.)	Report results	Summarize and visualize results	PEM_simulation (excel)	Project plans, schedules, resource (cost) diagrams, statistics, sensitivity charts etc.	Output: PEM_simulation.xls ->'Sim_results' sheet

Note: Steps 3-5. can be iterated as necessary.

Appendix G

Electronic supplementary materials

All supplementary materials and resources related to the dissertation can be found online on GitHub.

1. Project indicators github repository:
   https://github.com/novakge/project-indicators
2. Project database parsers github repository:
   https://github.com/novakge/project-parsers
3. Scripts and data for figures and analysis
   R scripts, data and analysis
   MATLAB scripts, data and analysis
4. Excel calculations and data
5. Excel simulation framework

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