THESIS SUMMARY

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

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1 Introduction

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 et al., 2010). A 84% of companies run projects simultaneously in a multiproject context (Lova et al., 2000). Several studies have shown that to increase the success of projects (Johnson, 2020), traditional project management approaches are increasingly being replaced by flexible approaches (Ciric et al., 2019; Hidalgo, 2019; Özkan and Mishra, 2019; Wysocki, 2019) not only in the IT field (Stare, 2014; Yasaman et al., 2022).

These approaches require flexible project plans with the possibility to restructure projects and reprioritize tasks according to the customer's requirements; however, 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, 2019; Tao and Dong, 2018). There are already a few matrix-based methods available for scheduling structurally flexible 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 no project database that supports the design, planning, and scheduling of flexible (multi)projects and no complexity and time- or resource-related indicator sets that are capable of characterizing flexible project plans. It is essential to provide both scholars and practitioners with such a database and set of indicators to allow studying flexible projects.

Therefore, the aim of this research was threefold. First, to specify a matrix-based method, which can handle single and multi-level projects, multiple execution modes, and flexible projects besides traditional ones. In addition, to collect existing heterogeneous project databases, including simulated (artificial) and real-life projects. Finally, to examine the effects of flexibility not only on the project structure but on the project demands as well.

2 Research questions

Considering the relevance and goals 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 solution for the single- and multiproject plans considering flexibility?

3 Related studies and research assumptions

Flexible multi-level project management and matrix-based scheduling

Agile project management has already gained popularity outside of software development context (Bergmann and Karwowski, 2018; Bianchi et al., 2018; Conforto et al., 2014; Owen et al., 2006) and adapts to uncertainty and changes even in later phases of a project. It focuses on prioritized items and requirements that offer the most business value in time, while traditional project management tries to predict and minimize change (Ciric et al., 2019) and emphasizes formal methods of planning. In a multilevel project environment, multi-projects, programs, and portfolios need to be scheduled. The projects vary in size, importance, required skills, and urgency, are in various stages of completion, and use the same pool of resources (Fricke and Shenbar, 2000). The management of multilevel projects presents a significant challenge that is fundamentally different from single project management (MacAskill and Guthrie, 2017).

Traditional network-based project planning tools (see e.g., Eisner, 1962; Kelley Jr, 1961; Roy, 1962; Wiest, 1981) are no longer able to fully support the strategic decisions of companies (Kosztyán, 2012). The few scheduling algorithms that address multilevel projects follow the traditional scheduling methodology, where the activities have a fixed order of execution (Pellerin and Perrier, 2019). 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 but with multiple domains (Danilovic and Browning, 2007). 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.

Resource-constrained (multi)project scheduling problem

The classical resource-constrained project scheduling problem (RCPSP) consists of a set of activities that need to be scheduled, subject to precedence and resource constraints, to optimize an objective function, e.g., minimizing the overall duration of a project. 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. 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 are also given in (Sánchez et al., 2022).

Flexibility of projects

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)), also in traditional project plans.

The second type is activity (i.e., task) or modal flexibility in which a task can be performed in several execution modes having different demands. Čapek et al. (2012), Kellenbrink and Helber (2015), and Tao and Dong (2018) defined RCP(M)SP with alternative activity chains resulting in RC(M)PSP-AC problems, while Hauder et al. (2020) extended it with 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. The latter two flexibility types appear typically, but not exclusively in agile projects (Kosztyán, 2015) and affect the logical structure of a project. Dependency and scope flexibility are together called structural flexibility, also examined within this study.

Project databases

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 developing new methods (Franco-Duran and Garza, 2019). 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).

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.

3.1 Research assumptions

By revisiting the research questions after reviewing 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. A simulation framework can be constructed to handle flexible dependencies and supplementary tasks.

4 Results and research theses

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

To unify the heterogeneous project databases, a matrix-based model is proposed based on the M^4 model by Kosztyán (2015, 2020), called the *unified matrix-based project-planning model* (UMP). It contains two mandatory (LD, TD) and four supplementary domains (see Figure 1).

Logic domain [LD]									Time domain [TD]			Cost domain [CD]			Quality domain [QD]			Nonrenewable resource domain [ND]							Renewable resource domain [RD]						
UMP'		Project$_A$			...	Project$_Z$																									
		P_{A1}	...	P_{An}	...	P_{Z1}	...	P_{Zn}	T_1	...	T_k	C_1	...	C_k	Q_1	...	Q_k	N_{11}	...	$N_{1\eta}$	...	N_{k1}	...	$N_{k\eta}$	R_{11}	...	$R_{1\rho}$	...	R_{k1}	...	$R_{k\rho}$
Project$_A$	P_{A1}	a_{11}	...	a_{1n}					t_{11}	…	t_{1k}	c_{11}	…	c_{1k}	q_{11}	…	q_{1k}	μ_{111}	...	$\mu_{11\eta}$	...	μ_{1k1}	...	$\mu_{1k\eta}$	r_{111}	...	$r_{11\rho}$	...	r_{1k1}	...	$r_{1k\rho}$
	⋮	⋮	⋱	⋮																											
	P_{An}	a_{n1}	...	a_{nn}																											
⋮	⋮				⋱				⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Project$_Z$	P_{Z1}					z_{11}	...	z_{1n}																							
	⋮					⋮	⋱	⋮																							
	P_{Zn}					z_{n1}	...	z_{nn}	t_{n1}	...	t_{nk}	c_{n1}	...	c_{nk}	q_{n1}	...	q_{nk}	μ_{n11}	...	$\mu_{n1\eta}$	...	μ_{nk1}	...	$\mu_{nk\eta}$	r_{n11}	...	$r_{n1\rho}$	...	r_{nk1}	...	$r_{nk\rho}$

FIGURE 1: 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.

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).

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.

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 project databases collected were heterogeneous both in terms of format and attributes. Building a parser tool for the current study in MATLAB (Mathworks, 2021), and using the UMP, it was possible to unify the databases summarized in Table 1. The corresponding **RA1** is thus accepted.

TABLE 1: 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

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

Since none of the project databases considers flexible project structures, these are generated from fixed structures. According to the specified flexibility parameter ($fp \in [0,1]$), the rate of mandatory tasks and fixed dependencies are converted by the flexible structure generator (FSG). Specified by the ratio fp, the values of cells containing 1s decreased from 1 in between 0 and 1. In this way, the rate of supplementary tasks and flexible dependencies can be set. 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 2.

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 2).

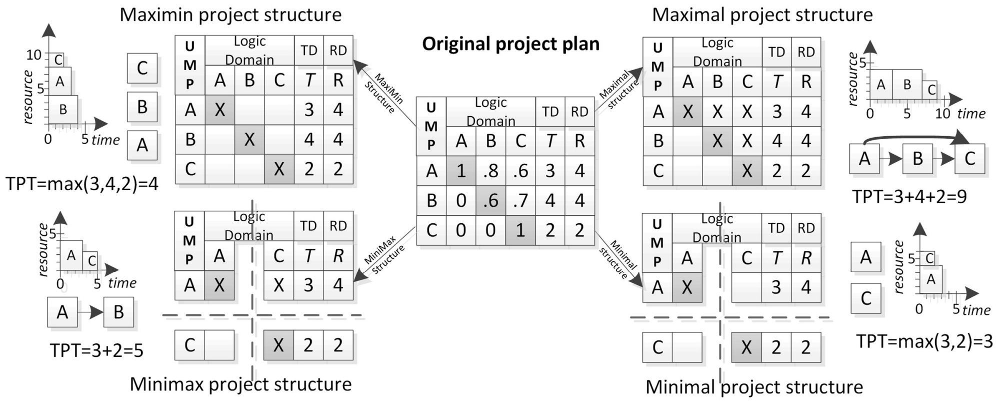


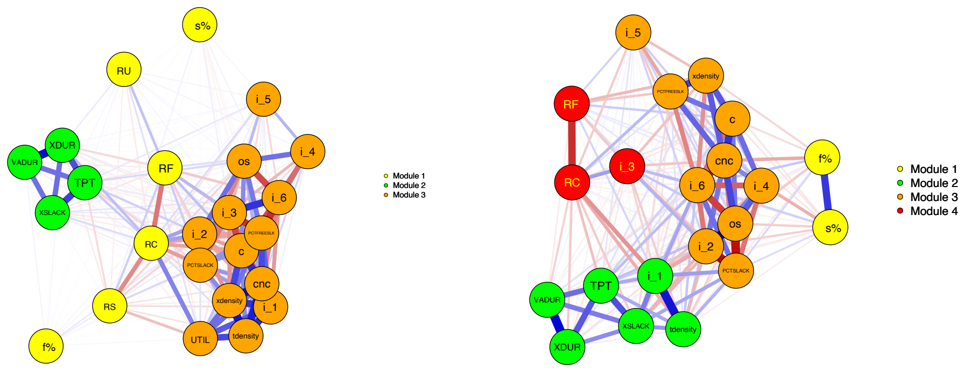
FIGURE 2: Minimal, maximal, minimax and maximin structures of the flexible project plan

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

After flexibility is set, the minimal, maximal (which is the original structure in this case), minimax and maximin structures can be added to the compound matrix-based project database (CMPD) database for further evaluation and to improve planning. As a result, **RA2** is accepted.

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

Using project related indicators on the fixed structures, with clustered correlation graphs and Leiden's modularity (Traag et al., 2019), the modules of indicators were formed. Figure 3 shows the clustered correlation graph between the indicators in the single-project database. 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 3: Clustered correlation graph 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.

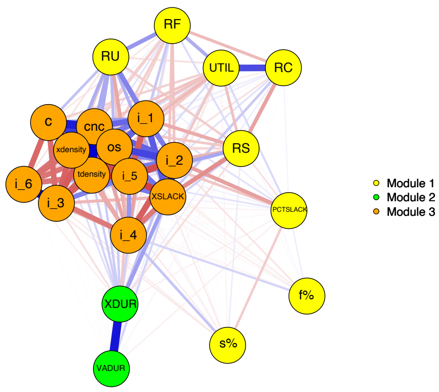
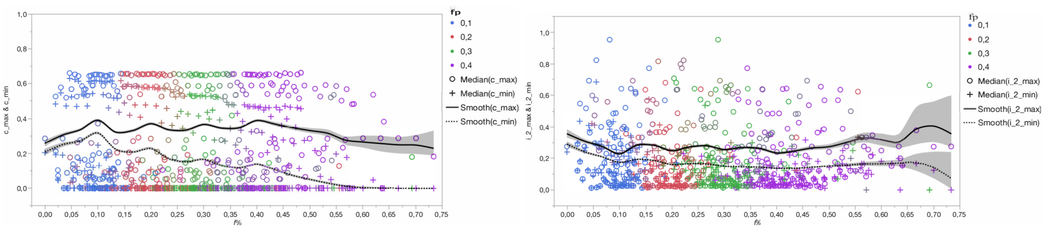


FIGURE 4: Clustered correlation graph of the multiple project database indicators. Note: indicators represent average values.

Figure 3 shows that several redundant indicators were highly correlating, especially the topological indicators (Module 3). In comparison, the proposed ($s\%$, $f\%$) flexibility indicators were located on the periphery (Module 2), so they need not to be merged. 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. 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.

Flexibility considerations not only expand the interval of the indicator values but also specify new value pairs for the coupled indicators. The interpretation ranges of the indicators of multiprojects are also broadened.
Regarding project topology, Figure 5 compares the complexity (C) and parallelization (I_2) indicator 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 5: Structural changes in complexity and parallelization

Figure 5 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 5(a)), as did the serial completions (see Figure 5(b)). These results are in line with the requirements of flexible project management approaches for reducing project complexity (Williams, 2010).

Figure 6 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 structural parameters on the horizontal axis.

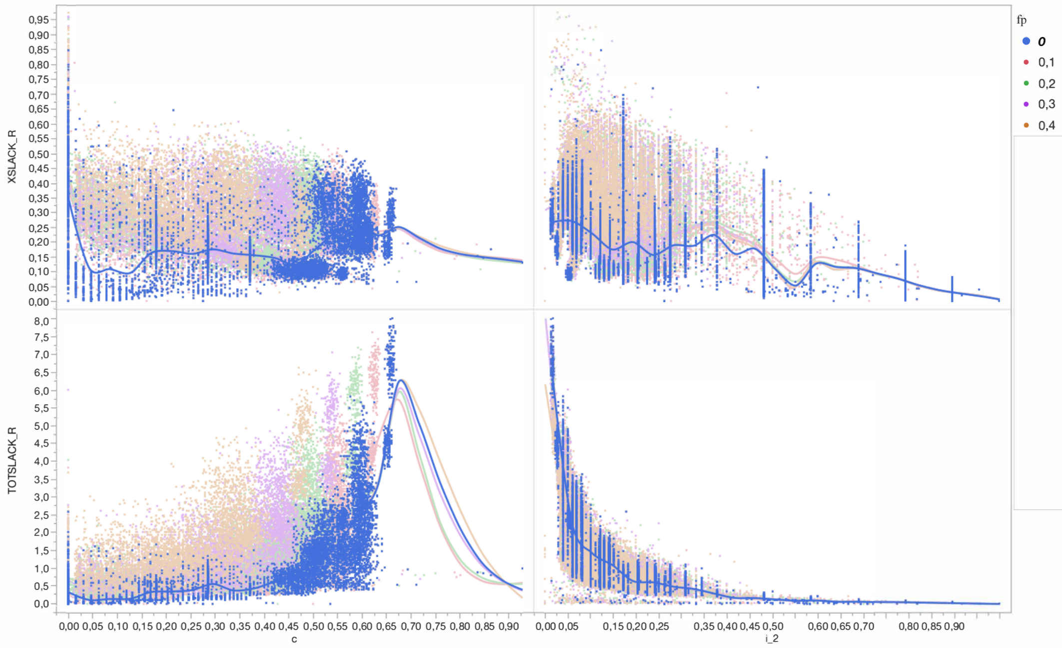


FIGURE 6: Flexibility effects on the relations between the time-related and complexity indicators

Figure 7 shows the relations between time- and resource-related indicators for the earliest start schedule. Considering the minimal structures of flexible projects, the resource constrainedness, and the obstruction factor are increased. These combinations of time-related and resource-related indicator values occurred only in flexible project plans.

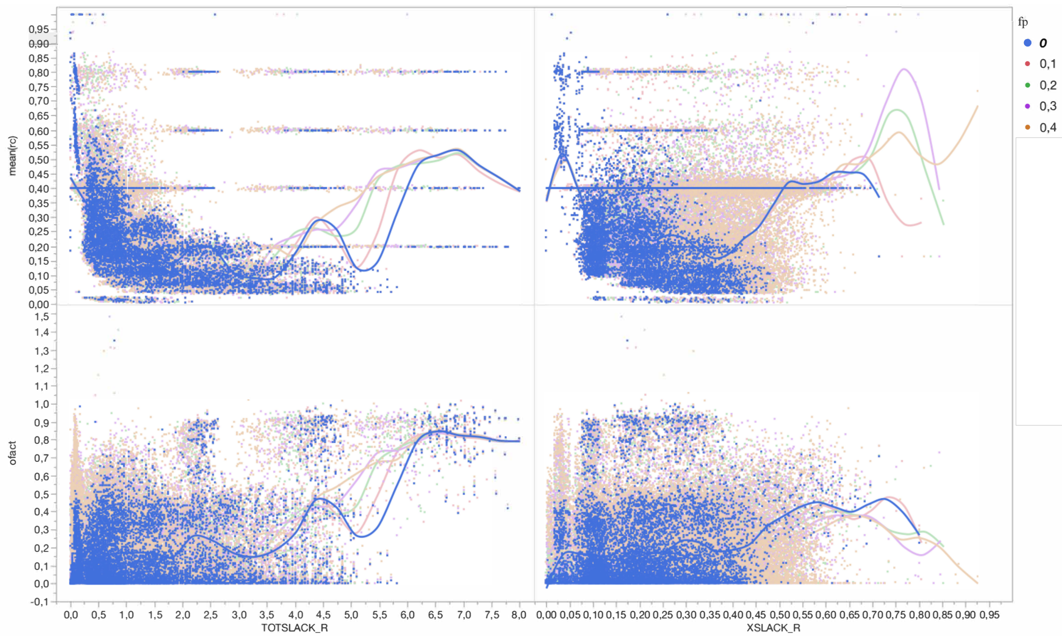


FIGURE 7: Flexibility effects on the relations between the time-related and the resource-related indicators

To analyse how flexible methods affect total project times (TPT) compared to traditional methods in the available groups of databases, 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 group. The coefficient of variation (CV) then used to show the extent of variability in relation to the mean of the population.

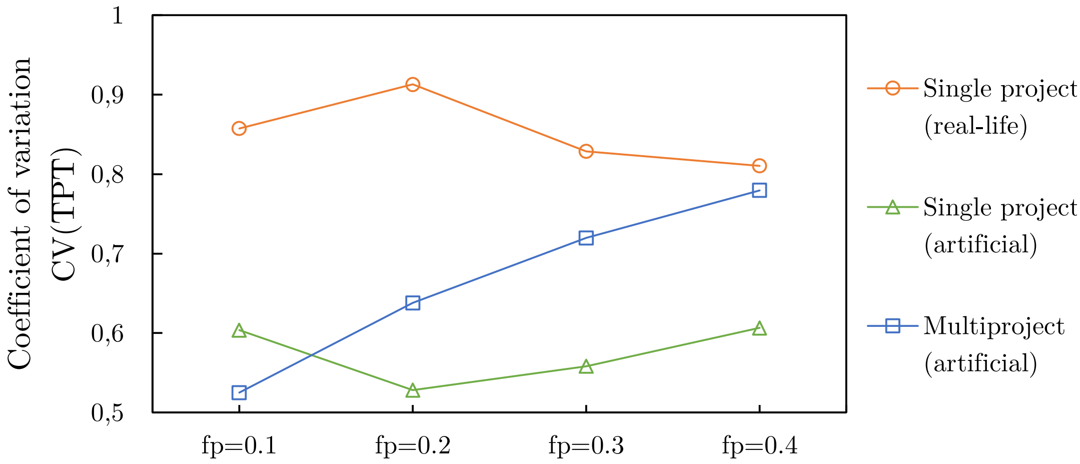


FIGURE 8: The coefficient of variations of average total project time by flexibility parameters of different database groups

As Figure 8 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. The shape of single projects (both artificial and real-life) seems inconclusive, while the variation of multiprojects average total project time is continuously increasing, which suggests that their durations are less predictable and hard to plan with. A regression model was also built to model the relationship between flexibility and multiproject durations besides existing descriptive statistics. Based on the evaluation of the different effects of flexibility, **RA3** is accepted.

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

To demonstrate that the flexible project plans (generated by FSG) can be solved to (near) optimality with existing algorithms, the NP-hard (Lenstra and Rinnooy Kan, 1978) resource-constrained multiproject scheduling problem (Pritsker et al., 1969) needed to be solved.

In the presented case study, an empirical multiproject plan was selected for this purpose. Due to the complex nature of the RCMPSP problems and a large number of activities with high resource-constrainedness, this study considered a metaheuristic optimization in line with the literature (Pellerin, Perrier, and Berthaut, 2020) to achieve near-optimal solutions. The commercial optimization engine OptQuest™ was used within the simulation framework developed as part of the current study.

From the flexible multiproject plan the fixed structures were generated. The optimization was carried out with the objective to minimize the average total duration of multiproject, respecting the resource constraints. The average duration of the maximal (original) structure have increased with 0.5% to respect (the originally violated) resource constraints, suggesting that the company's plan was rather optimistic. The maximin structure reduced the average multiproject duration with 5.14%, the minimax reduces approximately 24.77% and a 31.31% reduction could be achieved using the minimal structures, as summarized in Table 2. It was possible to find near-optimal solutions for all newly specified structures, which validates **RA4**.

TABLE 2: 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*

5 Research theses

Considering the research questions and assumptions with the corresponding results, four research theses were formulated.

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. It is possible to find a feasible, (near) optimal solution minimizing (multi)project duration or other objective functions while considering constraints on time, resources, and cost.

Results for research theses **RT1; RT2; RT3; RT3.1; RT3.2;** and **RT3.3** were published in Kosztyán, Novák, et al. (2022).

6 Summary and Conclusion

In the current dissertation a quantitative approach supplemented with a case study was provided to see the effect of flexibility on different indicators.

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 (priorized) activities and dependencies in a project often make decisions and estimates based solely on previous experience. The defined structures can enhance 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. The model, assumptions and results were validated with an empirical case study on an automotive company's development project.

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. 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. The proposed CMPD provides a wider range of values to test project schedules and resource allocation algorithms by introducing flexibility. The parsers, generators and indicators are available on GitHub. Table 3 summarizes the research.

6.1 Contribution to literature

No databases are currently available to help design and schedule (structurally) flexible projects. This research helps fill the gap. The contributions to the literature and practice 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 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 combined into a matrix-based project library. Further 5 multiproject databases, including 10 datasets were combined. Current research shows a way of extending the databases to address the flexible nature of the projects. The dissertation 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 also examines the effects of multiple modes for single projects and project flexibility.

6.2 Practical implications

The proposed matrix-based model addresses cost and nonrenewable demands and quality parameters and manages multiple completion modes and multilevel projects. It not only unifies heterogeneous databases but also allows the user to test both traditional and flexible project scheduling algorithms. The proposed simulation framework supports planning decisions with the characterization, comparison, and optimization of project plans. The open database solves the problem of data availability and reduces time to research and maintenance efforts while enabling collaboration between researchers and practitioners.

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7 The author's publications related to the topic

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TABLE 3: 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 solution for the single- and multiproject plans considering flexibility?*
RA4:	Flexible multilevel projects can be scheduled and near-optimal solutions can be found. 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. It is possible to find a feasible, (near) optimal solution minimizing (multi)project duration or other objective functions while considering constraints on time, resources, and cost.