THESIS SUMMARY

Synergy-Based Software Project Scheduling Problem: Formalization, Simulation, and Solution

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VESZPRÉM, HUNGARY

19 May 2021

Introduction and Research Questions

In the literature on software development, the common issue of resource allocation and task scheduling is referred to as the software project scheduling problem (SPSP) (see, e.g., Vega-Velázquez et al., 2018). While most of the software projects are managed in an agile framework (see, e.g., Wysocki 2011, 2019), the SPSP ignores the two main features of this approach: the flexibility of planning and the complexity of teamwork. The dissertation is focused on two possible approaches of extending the classical SPSP. First, a general form of the SPSP assumes fixed logic plans; however, applying flexible dependencies and using task priorities instead of fixed occurrences will result in more flexible project plans consistent with the agile approach. Despite the existence of agile project scheduling algorithms (see, e.g., Kosztyán, 2015), to date the SPSP has not yet been extended to incorporate this feature. Second, while software development projects and particularly software development projects using the agile approach (Wysocki, 2011) place a greater emphasis on teamwork than the traditional methods (Nerur et al., 2005), in the SPSP, employees are regarded as independent resources. This by definition assumes that the best (i.e., the most skilled) workers will perform tasks within the shortest timespan and with the highest quality; however, none of the extensions address the interdependence of resources. In order to make the SPSP more realistic and practical, and to understand the impact of synergies on project scheduling, the dissertation seeks answers to the following research questions (**RQs**).

Research Questions:

RQ$_1$: Is it possible to determine a scheduling problem for traditional and flexible project planning environments that considers not only the skills of human resources but also the synergies between them?

$\mathbf{RQ}_2$: Is it possible to develop a network- or matrix-based project scheduling model that takes into account the flexibility of project plans, the skills of human resources as well as the synergies between them?

$\mathbf{RQ}_3$: Is there a(n optimal) solution for scheduling a flexible software project plan that considers the synergies between resources?

$\mathbf{RQ}_4$: Is it possible to develop a simulation framework to examine the impact of the synergies between resources, the structures of synergy networks, the skills of human resources as well as the size, flexibility, and constraints of the project on the implementation of the project schedule?

Related Studies and Research Assumptions

Agile development methods have been widely used in software engineering over the last decade (Lindsjørn et al., 2016). Contrary to the traditional planning approach, this methodology focuses on "individuals and interactions over processes and tools", "working software over comprehensive documentation", "customer collaboration over contract negotiation", and "responding to change over following a plan" (Fowler et al., 2001, p. 2).[1] Since it emphasizes teamwork more than traditional development methods do (Nerur et al., 2005), it is not surprising that the tasks of allocating human resources and scheduling play a critical role in the success of software development projects (see, e.g., Jalote and Vishal, 2003), and consequently, in the competition in the information technology (IT) industry (Nan and Harter, 2009). To reduce development costs and beat the market, companies have to make reliable project plans; however, efficient allocation of workers is a particularly difficult and challenging problem, particularly for medium- to large-scale projects (see, e.g., Minku et al., 2013). For instance, in China alone, more than 40% of software projects were unsuccessful due to incoherent planning of project tasks and human resources (Ding and Jing, 2003).

[1] Agile methodology is used as an umbrella term to describe a number of development methods (Dybå and Dingsøyr, 2008; Dingsøyr et al., 2012).

The software project scheduling problem (SPSP) – which combines resource allocation and task scheduling in software projects – is related to the resource-constrained project scheduling problem (RCPSP) (Alba and Chicano, 2007; Vega-Velázquez et al., 2018) – or more specifically, to the multi-skill resource-constrained project scheduling problem (MS-RCPSP) (Myszkowski et al., 2019; Tirkolaee et al., 2019). Alba and Chicano (2007) defined the differences between the SPSP and the RCPSP as follows. Firstly, in the SPSP there is a project cost and a cost associated with the workers, which must be minimized (in addition to the project duration). Moreover, while in the RCPSP there are several types of resources, while the SPSP has only one (the employee) with several possible skills. Finally, while each activity in the RCPSP requires different quantities of each resource, skills in the SPSP are not quantifiable entities. Following Alba and Chicano (2007), these differences make the SPSP more realistic than the RCPSP, since it includes the concept of an employee with a salary and personal skills, also capable of performing several tasks during a regular working day. Note that the SPSP shows more similarities to the MS-RCPSP than to the RCPSP, however, there are also some differences between the first two. For instance, unlike in the MS-RCPSP, resources in the SPSP can perform multiple tasks over time, and it also takes into account the dedication of employees to activities (see, e.g., Myszkowski et al., 2015, 2017; Laszczyk and Myszkowski, 2019).

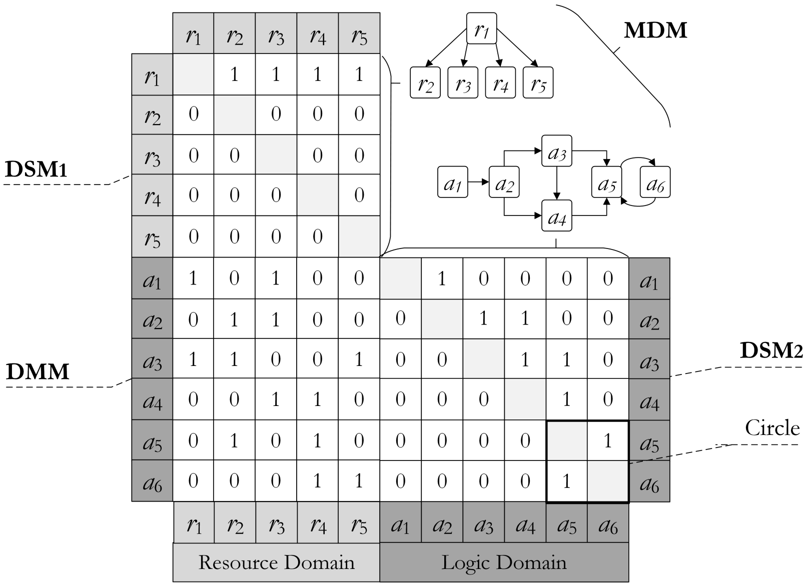
The efficiency of solving the SPSP usually depends on several factors. On the one hand, the development process should be as short as possible, thus allowing the allocation of resources to other profitable processes as soon as possible. On the other hand, the associated cost should be minimal. This multi-objective nature makes planning even more complicated and, as a result of the increasing size of software projects, makes manual scheduling almost impossible (Shen et al., 2018).[2] Research

[2] The SPSP is an NP-hard problem, which means that there is no known algorithm that can solve the problem in polynomial time (see, e.g., Islam et al., 2019).

on this topic has intensified rapidly in recent years; however, due to the abovementioned reason, such research has mostly focused on the technical improvements of computer-aided planning (see, e.g., Chicano et al., 2011; Di Penta et al., 2011; Luna et al., 2014). To solve the SPSP, Coello et al. (2006) and Myszkowski et al. (2019) propose several meta-heuristics, while Chicano et al. (2011) and Luna et al. (2014) compare accuracy and scalability of these algorithms. Chicano et al. (2011) and Luna et al. (2014) observe that the algorithm called Pareto archived evolution strategy (PAES) (Knowles and Corne, 2000) has the best scalability and obtains the best approximate Pareto sets, while the most widely used non-dominated sorting genetic algorithm II (NSGA-II) (Deb et al., 2002) and strength Pareto evolutionary algorithm 2 (SPEA2) (Zitzler et al., 2001) are examples of the least accurate solvers in general. Nevertheless, PAES is outperformed by NSGA-II, SPEA2 and several recent algorithms, such as the multi-objective cellular genetic algorithm (MOCell) (Nebro et al., 2007) in high-cost short-duration project scheduling (Luna et al., 2014).

Although most software projects are handled in an agile project management (APM) framework (see, e.g., Wysocki 2011, 2019), the general form of SPSP assumes fixed logic plans. Unlike traditional project planning techniques such as the critical path method (CPM) or the project/program evaluation and review technique (PERT), matrix-based methods provide a flexible planning environment and support the agile planning approach. Most of these methods are based on the so-called dependency/design structure matrix (DSM) developed by Steward (1981). The DSM is a binary square ($n \times n$) matrix that represents the strict successors of the project activities, and contrary to the majority of the network planning techniques, the circles in the dependency structure can be identified and handled by this method. To augment the DSM method, Danilovic and Browning (2007) formalized the domain mapping matrix (DMM), which compares two DSMs from two different project domains. Contrary to a DSM, a DMM is a rectangular ($m \times n$) matrix, where m is the size of the first DSM and n is the size of the second. Another matrix proposed by Gorbea et al. (2008), the so-called the multi-domain matrix (MDM), is a fusion of DSM and DMM that allows for the integration of numerous different domains in one model (Deubzer et al., 2008) (see Fig. 1).

FIGURE 1. Multi-domain matrix (MDM)
(Source: own figure)



In addition to flexible logical plans, the SPSP also overlooks another important feature of the agile approach, the impact of project team members on each other's performance (see, e.g, Rodriguez-Repiso et al., 2007). While most psychological and sociological approaches emphasize the complexity of the project team (see, e.g., Hsu et al., 2016), none of the applied models can handle the interdependence of employees. According to the literature related to the effectiveness of project teams, formal and informal relationships between employees can be a source of positive or negative synergies that significantly affect the performance of the project team (Ahuja et al., 2003) or, consequently, the outcome of the project (Sanchez et al., 2017). The structure of these relationships are often studied by using sociometric networks, however, the results in this area are contradictory. While Ahuja et al.

(2003) and Cummings and Cross (2003) emphasize the beneficial impact of decentralized, less hierarchical structures on performance, Sanchez et al. (2017) found a positive connection between the formal power of the project manager, as well as the smaller, less dispersed teams, and the success of IT projects. Although employee interdependencies have a significant impact on project outcomes – especially for (software) projects managed by an APM approach –, no planning method has yet been developed to study or apply the phenomenon in practice.

Based on a review of the literature, one research assumption is formulated for each of the four research questions (**RQs**). The four research assumptions (**RAs**) of the dissertation are as follows.

Research Assumptions:

RA_1: The classical software project scheduling problem can be extended by considering flexible task dependencies and synergies between resources.

RA_2: The multi-domain matrix (MDM) can be specified to a flexible multi-domain matrix whose interconnected domains model the flexible project plan, the skills of human resources as well as the synergies between them.

RA_3: Using metaheuristic algorithms, it is possible to find a feasible solution to the project scheduling problem that takes into account flexible task dependencies and synergies between resources.

RA_4: By supplementing existing or generated project databases with flexible task dependencies and resource synergies, it is possible to create a simulation environment to examine the impact of human resource synergies and skills, as well as project size, flexibility, and constraints, on project feasibility.

Results and Research Theses

RQ_1: Is it possible to develop a scheduling problem for traditional and flexible project planning environments that considers not only the skills of human resources but also the synergies between them?

In line with the $\mathbf{RA}_1$, the classical software project scheduling problem (SPSP) was extended by considering flexible task dependencies and pairwise synergies between resources. The so-called synergy-based software project scheduling problem (SSPSP) thus defined reflects the APM approach widely used in software development practice, and consequently outlines a more realistic planning problem than the classical SPSP.

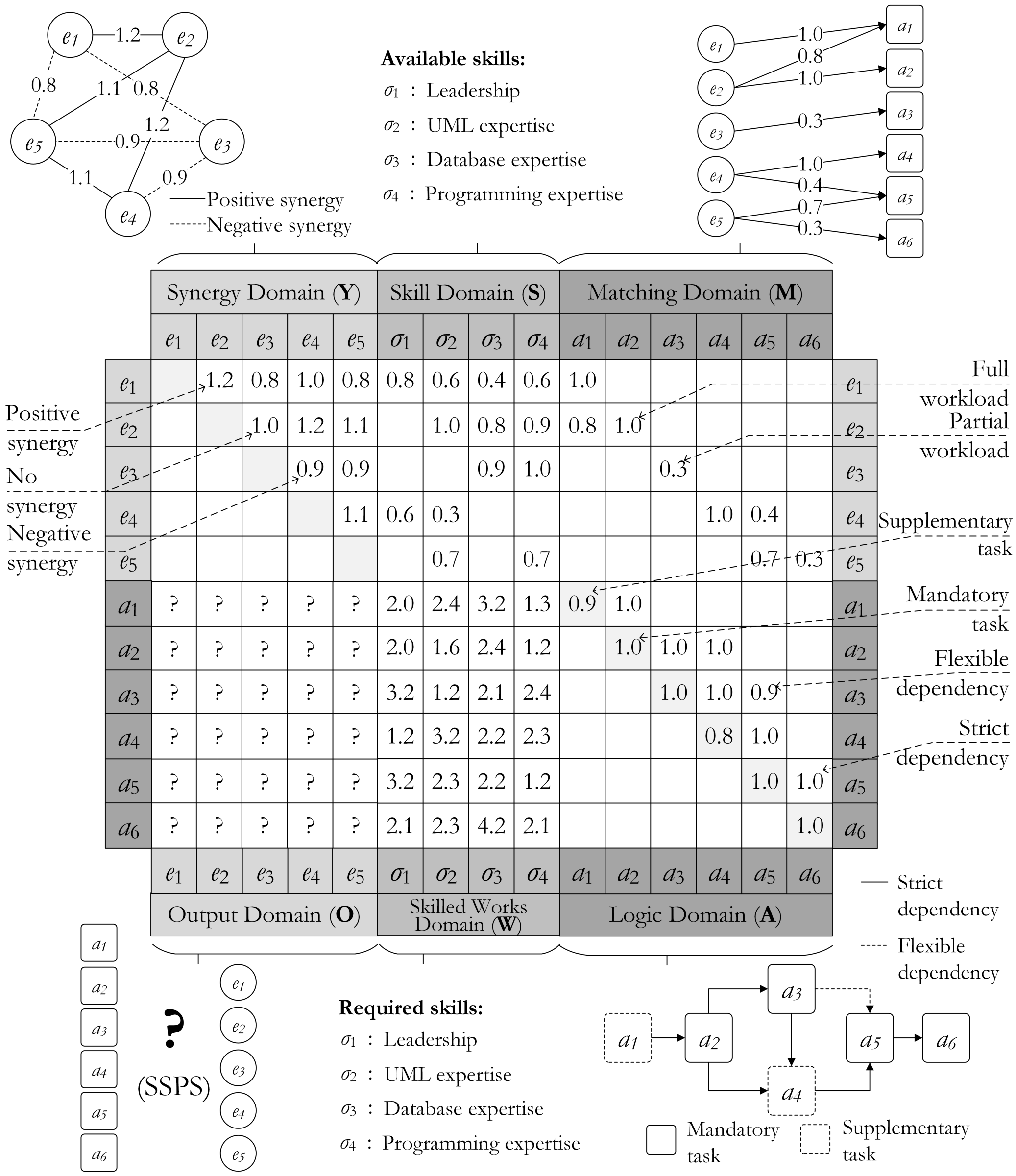
$\mathbf{RQ}_2$: Is it possible to develop a network- or matrix-based project scheduling model that takes into account flexible project plans, the skills of human resources as well as the synergies between them?

To model both classical and synergy-based SPSPs, I proposed an extended form of the MDM (see Fig. 1) according to the $\mathbf{RA}_2$. The new, so-called synergy-based multi-domain matrix (SMM) contains multiple interconnected domains that model the flexible logical structure of the project, the amount of (skilled) work to be performed within the project, the skills of human resources and the positive and negative pairwise synergies between them, as well as the maximum resource assignments (see Fig. 2).

$\mathbf{RQ}_3$: Is there a(n optimal) solution for scheduling a flexible software project plan that considers the synergies between resources?

Using the proposed simulation framework (SynASF) and the proposed hybrid genetic algorithm (SynAPS), $69,984$ classical and synergy-based SPSPs were simulated and solved with respect to the applied complex objective (or target) function and applied constraints. For all optimization problems, SynAPS found a good feasible solution. Not only does this verify the $\mathbf{RA}_3$, but it also shows that by applying the proposed multi-domain model (SMM) and the SynAPS, both classical and synergy-based SPSPs can be solved even in a flexible project planning environment.

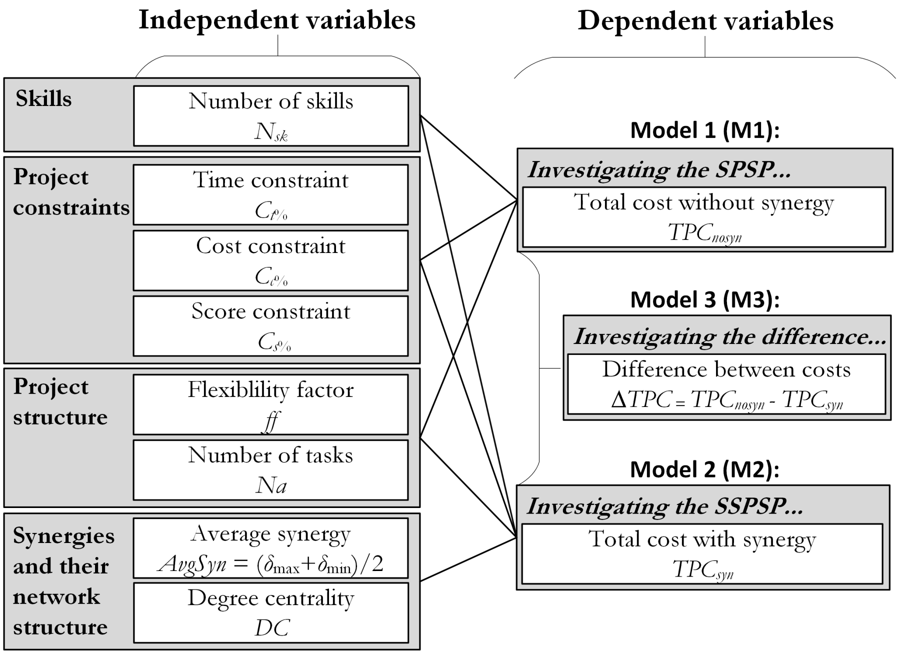
FIGURE 2. Synergy-based multi-domain matrix (SMM)
(Source: own figure)



$\mathbf{RQ}_4$: Is it possible to develop a simulation framework to examine the impact of the synergies between resources, the structures of synergy networks, the skills of human resources as well as the size, flexibility, and constraints of the project on the implementation of the project schedule?

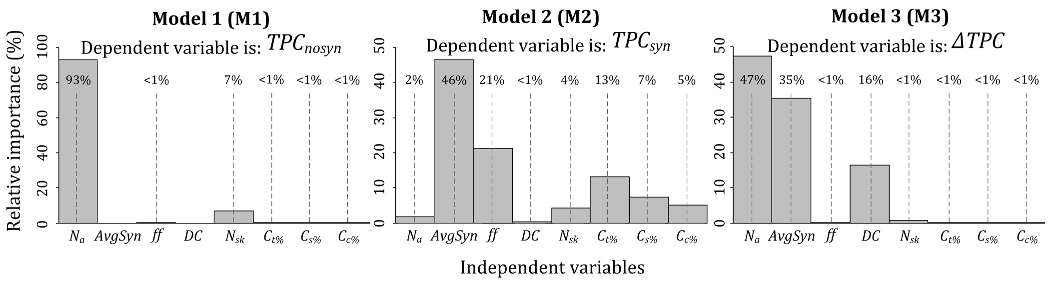
In order to decide whether the proposed simulation framework is suitable for performing the examination referred to in the $\mathbf{RQ}_4$, I analyze the optimization results of $69,984$ classical and synergy-based SPSPs simulated by the SynASF. The analysis is based on the research model presented in Fig. 3.

FIGURE 3. Research model
(Source: own figure)



This model is focused on three cases: the case of SPSP in which synergies are ignored (M1), the case of SSPSP in which synergies are taken into account (M2), and the difference between these two approaches (M3). Since the cost of the project is a function of duration and the employees' salary, in the main text, TPC_{nosyn}, TPC_{syn} and ΔTPC are considered as the only dependent variables. During the analysis of the optimization results, I employ the regression tree ensemble model of the Matlab Regression Learner App (MathWorks, 2019b). Furthermore, 10-fold cross-validation was used, and the hyperparameters were tuned by Bayesian optimization. Fig. 4 shows the relative importance of independent variables (predictors) for all three cases.[3]

FIGURE 4. Relative importance of various predictors
(Source: own figure)



In case of the SPSP (see Fig. 4 – M1), the size of the project (N_a) and the various skills of employees (N_{sk}) are the main factors impacting project costs; however, if synergies between two employees are considered (see Fig. 4 – M2), the principal effect is due to the average pairwise synergy ($AvgSyn$) itself. In this case, changes in the time, score and cost constraints ($C_{t\%}, C_{s\%}, C_{c\%}$) and flexibility ($ff$) also influence the project cost, while the previously important size (N_a) and skills (N_{sk}), as well as degree centrality (DC), have only a small impact on the cost. Model 3 specifies the parameters that explain the cost differences of these two approaches. According to this model, the project size (N_a) has the highest explanatory power of 47%, followed by the average synergy ($AvgSyn$ – 35%) and the structural parameter (DC – 16%). These results have two main implications. First, the synergy-related parameters have a very strong effect on projects' costs even though, based on the current parameterization of the model, the interdependence of two employees can only change their performance to a relatively small extent. Second, the high

[3] The relative importance is calculated using the *predictorImportance* Matlab function (see MathWorks, 2019a).

impact of the structural parameter (DC) appears to be consistent with the relevant literature.

To determine, which structures of synergy networks reduce the project cost the most, I examine how ΔTPC (see Fig. 3 – M3) is influenced by the sociometric structure and how their relation changes based on the structural parameter (DC; the respective results are shown in shades of gray) or project flexibility (ff – Case $1-3$) varies (see Fig. 5).

FIGURE 5. Effect of sociometric structures on the project cost
(Source: own figure)

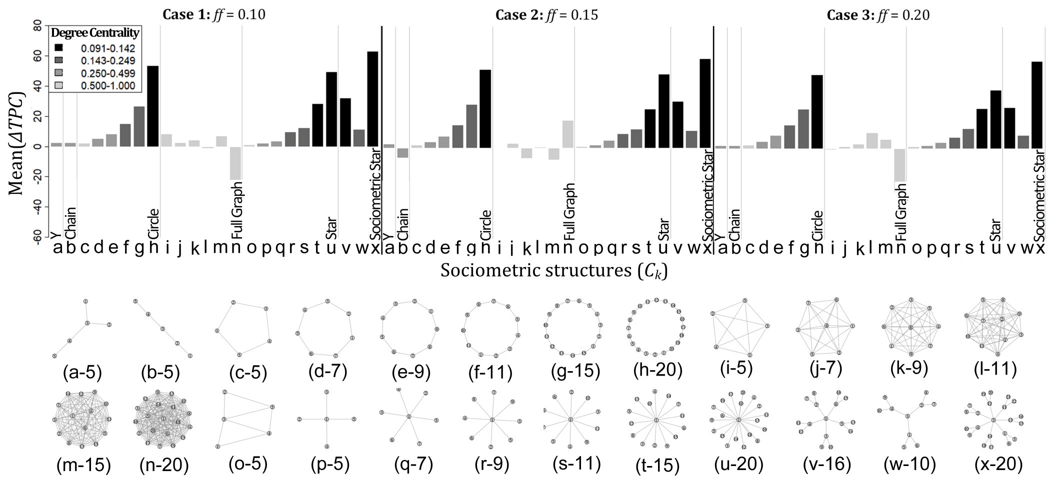


Fig. 5 shows that structures with low degree centrality (DC) generally lead to a greater reduction in the project cost; however, the veracity of this statement depends on the topology of the sociometric network. Although I observe that the flexibility of the project (ff) has a negligible effect on ΔTPC (see Fig. 4), I find that chain and full graph networks are highly sensitive even to insignificant changes of this parameter (see Fig. 5 Case 1-3). In some cases involving these topologies, the TPC_{syn} is greater than the $\text{TPC}_{\text{nosyn}}$, resulting in a negative ΔTPC. Furthermore, in the case of the networks randomly containing favorable and unfavorable synergies, the most decentralized topology (the full graph) leads to the worst results because of its high sensitivity to negative synergies. On the one hand, these findings are contrary to that of Sparrowe et al. (2001), since, in their model, decentralized networks (such as circle and full graph networks) are unable to reduce costs by an amount greater than that of the centralized networks (such as star and sociometric star networks). On the other hand, it is in line with the empirical findings of Sanchez et al. (2017), who observed that the formal power of the project manager as well as the smaller, less dispersed teams have a positive impact on the outcome of projects. Note that not only did this analysis prove the $\mathbf{RA}_4$, but it also pointed out some important correlations regarding the impact of employee synergies on the project schedule.

Based on the presented results, one research thesis is formulated for each of the four research questions ($\mathbf{RQ}$s) and assumptions ($\mathbf{RA}$s). The four theses ($\mathbf{RT}$s) of the dissertation are the following.

Research Theses:[4]

$\mathbf{RT}_1$: The proposed synergy-based software scheduling problem (SSPSP) extends the classical software scheduling problem (SPSP) to take into account the flexibility of project plans, as well as the pairwise synergies between resources.

$\mathbf{RT}_2$: The proposed synergy-based multi-domain matrix (SMM) contains multiple interconnected domains that model the flexible logical structure of the project, the amount of (skilled) work to be performed within the project, the skills of human resources and the positive and negative pairwise synergies between them, as well as the maximum resource assignments. The proposed matrix is able to model all solutions of both the classical (SPSP) and the synergy-based (SSPSP) software scheduling problems.

$\mathbf{RT}_3$: The proposed synergy-based agile project scheduling algorithm (SynAPS) finds a feasible solution for both the classical (SPSP) and the synergy-based (SSPSP) software project scheduling problems with respect to the given objective function (that minimizes the duration and cost of the project while simultaneously maximizing its score) and given constraints (in relation to the duration, cost, resource, and score of the project).

[4] The theses are based on Kosztyán et al. (2021a) and Kosztyán et al. (2021b).

$\mathbf{RT}_4$: The proposed synergy-based agile simulation framework (SynASF) is suitable for examining the impact of pairwise synergies between resources, synergy structures, skills as well as the size, flexibility, and constraints of the project on the implementation of project scheduling. According to the synergy-based agile simulation framework (SynASF):

- $\mathbf{RT}_{4.1}$: The costs of projects are most sensitive to the pairwise synergies of human resources.
- $\mathbf{RT}_{4.2}$: The impact of pairwise synergies on project costs is mainly influenced by the size of the project, the average pairwise synergy, and the structural parameter (degree centrality) of the synergy network.
- $\mathbf{RT}_{4.3}$: Synergy networks with low degree centrality lead to a greater reduction in the project cost; however, the impact of synergies is also influenced by the topology of networks. The highest costs are obtained by the synergy networks with the most decentralized topology (full graph) because of their high sensitivity to negative synergies.

Conclusion

As a planning and decision-supporting tool, the proposed method may be particularly beneficial for software development companies that adopt the APM approach and already have the expertise and technical background to solve a complex software project scheduling problem (SPSP). In contrast to other approaches found in the literature, the new multi-domain method (SMM) supports flexible project planning, and provides an opportunity to model employee interdependencies by introducing the concept of pairwise synergies. As it is not limited to one source of synergy, it can be used to model the impact of different synergy sources – such as the formal structure of the team, communication between team members, team roles, and shared knowledge or experience – on the implementation of the project schedule, depending on the available data and the characteristics of the projects managed by the company. In addition to its practical advantages, it may also be suitable for bridging the gap between people-centered and methodological research in the field of human resource allocation and project team composition.

The research questions ($\mathbf{RQ}$s) and assumptions ($\mathbf{RA}$s), as well as the theses ($\mathbf{RT}$s) formulated for each are summarized in Table 1.

TABLE 1. Research questions, assumptions and theses
(Source: own table)

N*	Description
$\mathbf{RQ}_1$	Is it possible to determine a scheduling problem for traditional and flexible project planning environments that considers not only the skills of human resources but also the synergies between them?
$\mathbf{RA}_1$	The classical software project scheduling problem can be extended by considering flexible task dependencies and synergies between resources. **(Verified)**
$\mathbf{RT}_1$	The proposed synergy-based software scheduling problem (SSPSP) extends the classical software scheduling problem (SPSP) to take into account the flexibility of project plans, as well as the pairwise synergies between resources.
$\mathbf{RQ}_2$	Is it possible to develop a network- or matrix-based project scheduling model that takes into account the flexibility of project plans, the skills of human resources as well as the synergies between them?
$\mathbf{RA}_2$	The multi-domain matrix (MDM) can be specified to a flexible multi-domain matrix whose interconnected domains model the flexible project plan, the skills of human resources as well as the synergies between them. **(Verified)**
$\mathbf{RT}_2$	The proposed synergy-based multi-domain matrix (SMM) contains multiple interconnected domains that model the flexible logical structure of the project, the amount of (skilled) work to be performed within the project, the skills of human resources and the positive and negative pairwise synergies between them, as well as the maximum resource assignments. The proposed matrix is able to model all solutions of both the classical (SPSP) and the synergy-based (SSPSP) software scheduling problems.
$\mathbf{RQ}_3$	Is there a(n optimal) solution for scheduling a flexible software project plan that considers the synergies between resources?
$\mathbf{RA}_3$	Using metaheuristic algorithms, it is possible to find a feasible solution to the project scheduling problem that takes into account flexible task dependencies and synergies between resources. **(Verified)**
$\mathbf{RT}_3$	The proposed synergy-based agile project scheduling algorithm (SynAPS) finds a feasible solution for both the classical (SPSP) and the synergy-based (SSPSP) software project scheduling problems with respect to the given objective function (that minimizes the duration and cost of the project while simultaneously maximizing its score) and given constraints (in relation to the duration, cost, resource, and score of the project).
$\mathbf{RQ}_4$	Is it possible to develop a simulation framework to examine the impact of the synergies between resources, the structures of synergy networks, the skills of human resources as well as the size, flexibility, and constraints of the project on the implementation of the project schedule?
$\mathbf{RA}_4$	By supplementing existing or generated project databases with flexible task dependencies and resource synergies, it is possible to create a simulation environment to examine the impact of human resource synergies and skills, as well as project size, flexibility, and constraints, on project feasibility. **(Verified)**
$\mathbf{RT}_4$	The proposed synergy-based agile simulation framework (SynASF) is suitable for examining the impact of pairwise synergies between resources, synergy structures, skills as well as the size, flexibility, and constraints of the project on the implementation of project scheduling. According to the synergy-based agile simulation framework (SynASF): $\mathbf{RT}_{4.1}$: The costs of projects are most sensitive to the pairwise synergies of human resources; $\mathbf{RT}_{4.2}$: The impact of pairwise synergies on project costs is mainly influenced by the size of the project, the average pairwise synergy, and the structural parameter (degree centrality) of the synergy network; $\mathbf{RT}_{4.3}$: Synergy networks with low degree centrality lead to a greater reduction in the project cost; however, the impact of synergies is also influenced by the topology of networks. The highest costs are obtained by the synergy networks with the most decentralized topology (full graph) because of their high sensitivity to negative synergies.

***Notations:** $\mathbf{RQ}$: research question, $\mathbf{RA}$: research assumption, $\mathbf{RT}$: research thesis.

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