Importance of System Dynamics in Project Management – a Collection of Case Studies

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ABSTRACT

System dynamics is a modelling approach that has the ability to represent dynamic behaviour of complex systems. Such a system can be used in the context of managing a project. Project management is of great importance for companies and their projects, making it essential to carry this out properly. Using system dynamics for project management can bring advantages. However, there is still a research gap in the sense that there is no overview of applications of system dynamics that show how the modelling approach can aid project management. This research thus dives into existing literature and case studies to create this overview. The value of the research brings insight into which project phases can benefit from system dynamics modelling, and whether there are certain industries where system dynamics is especially useful. The conclusion is that the modelling approach is beneficial for all sorts of projects, especially during the initiation and progress phases.

Keywords

System Dynamics, Project Management, Project Phases, Project Resources, Subsystems

1 INTRODUCTION

Project management is the key to control: for projects in general, but especially for IT projects. It is responsible for keeping projects within certain boundaries like cost, duration, and quality, also known as the "iron triangle" of project management [18]. To do so, estimation, planning, and monitoring a project's progress are of great importance [20]. One way to achieve this is with the use of traditional project management models. These focus on defining a project work structure and creating detailed schedules and budgets to monitor and control performance. This is done throughout the project's life cycle and assesses the project status by comparing the current state to the expected one [19]. But it is argued that this approach has some problems and limitations. The most pressing issue is that the influence of human factors is not incorporated [20]. Actually, the current problem is more the other way around, as traditional management is based on human perceptions of the project's status and thus a lot of errors remain unperceived [19]. Next to this, traditional techniques support the operational planning in detail, but this is only after key strategic decisions and thus possible mistakes have already been made [19]. So, it comes into play relatively late in the process. These traditional models also fail to capture dynamic interactions between technical development and management policies [20]. This is because they view a project as something static, or they "take a partial, narrow view in order to allow managers to cope mentally with the complexity" ([15], p. 238). Additionally, because of rising complexity of modern technologies, organizations, and markets [19, 21], traditional models are not able to provide a quick and reliable strategic analysis to capture the project in detail [20]. As a result, poor management can lead to an increase in costs more rapidly than any other factor. Most large, complex development projects tend to have huge cost and schedule overruns because of poor project management [15, 19–21].

As a response to these limitations, system dynamics for project management has been proposed as a solution. The base of system dynamics was already introduced by Forrester in 1961 [8]. It facilitates understanding processes and the selection of interventions, creates insights into dynamics, simulates the actual situation, and helps understand the impact of decisions. The model represents dynamic behaviour, even of complex systems, and takes feedback processes into account [19, 21, 25, 29]. The definition of a complex system is here "a high-order, multiple-loop, non-linear feedback structure" ([25], p. 7). For example, a project has several components that interact with each other and provide causal feedback loops. A system dynamics model of a project should take the following elements into account [21]: (1) (human) resources; (2) the software production process: the execution of tasks, progress checks and quality control; (3) project planning: the start and expected completion date, schedule; and (4) project control: the collection of progress data and information (rescheduling, recruitment, or replacement).

As a special type of projects we have IT projects, which are often part of larger portfolios, so they can have interrelations regarding the sharing of resources between projects [1, 21]. To make it even more complex, they frequently deal with cross-functional processes. Regularly, problems arise from competition between these projects regarding resources, as people and other assets are seldom available when required. An example is that financial resources force limitations on employees and equipment [1]. Especially in these multi-project situations, system dynamics models create insights in the dynamics of the software development process [20].

2 PROBLEM STATEMENT

Successful projects require proper project management, which can benefit from the use of system dynamics. Often failures are blamed on external forces, but bad project management is a significant factor for these project failures [19, 23]. As of now, there is still a research gap between abstract frameworks and concrete evidence on the use of system dynamics for (IT) project management. When going through literature systematically, there is almost nothing to be found and most of the researches use simulations of mock-up projects instead of real applications. There is no clear collection of applications

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that show proof of the concept, so that is what this research looks into.

The main goal of the research is to provide an overview of projects from literature that shows for which project phases system dynamics was used and turned out to be (not) useful. This overview will be created for both the project phases as defined in Rogetzer and Wijnhoven [21] (initiation, progress, completion) and the subsystems created by Abdel-Hamid [1] (human resource management (HRM), software production, control, planning), which are further discussed in Section 4.1. As another goal, it is interesting to see where system dynamics is already in use and which industries can benefit most.

To get to these expected results, the following research question is the base of the research: ***What are the applications of system dynamics in project management?***

As an aid to answer this rather broad research question, the following sub-research questions (SRQ) have been formulated:

- **SRQ1:** In which project phases (initiation, progress, completion) is system dynamics used?
- **SRQ2:** In which of the major subsystems (HRM, software production, control, planning) is system dynamics used?
- **SRQ3:** Which industries benefit from the use of system dynamics for project management?

3 METHODS OF RESEARCH

To get an answer to these questions this research is divided into a few building blocks. The first one is a literature review on the use of system dynamics for (IT) project management. This literature review is non-systematic and based on Rogetzer and Wijnhoven [21]. A backward search allows for more details on certain topics to create the background on system dynamics. This is extended to the collection of cases. These are either successful applications of system dynamics, or cases that demonstrate that system dynamics had to be used differently. The case study collection is a combination of systematic and non-systematic literature search. After using the search query “"system dynamics" AND project AND management” on Google Scholar, [16] by Lyneis and Ford was found to form the base of the case collection, as it demonstrates applications of system dynamics in project management. However, the focus of that research lies on the goal of the system dynamics use, and does not take any phases or subsystems into account. With a backward search the other articles that discuss these applications are found and they are assessed as to whether they fit the scope. This means that they (1) apply system dynamics for project management and (2) have a relation to IT. Additionally, a systematic literature search is done to find more cases. The third step is to analyse the case studies according to the sub-research questions. For SRQ1 - In which project phase(s) is system dynamics used? – the cases are categorized in the three phases according to the description by Westland [27]. For SRQ2 – In which of the major subsystems is system dynamics used? – the same is done as for SRQ1 but then using the characteristics that Abdel-Hamid [1] describes for each of the four major subsystems. For the last question, SRQ3 - Which industries benefit from the use of system dynamics for project management? – a classification is made. An example of this can be automotive, civil construction, software, or healthcare. This together creates the overview that answers the main research question.

4 LITERATURE REVIEW

The literature review is based on three research streams: project management, system dynamics, and their application. These streams are combined in practice and discussed in the following sections.

4.1 Project Management

Project management is typically done in phases. System dynamics can be used in all these phases, as demonstrated by Rogetzer and Wijnhoven [21]. In their paper, they use the project life-cycle. Westland [27] describes the project life-cycle, which consists of four phases: (1) project initiation: used to identify a business problem or opportunity; (2) project planning: ensure that activities are performed in the execution phase; (3) project execution: construct and present the deliverables of the project; (4) project closure: winding up the project and review.

To follow the adaptation by Rogetzer and Wijnhoven [21], the first two life-cycle phases are combined into the initiation phase in this research. They provide a high-level illustration that demonstrates how project management can be modelled with system dynamics, as shown in Figure 1 [21]. The initiation, progress, and completion phase [21] are interchangeable with the initiation, execution, and closure phase [27]. For the overview in the results (Section 5.1) this paper will use the initiation, progress, and completion phase.

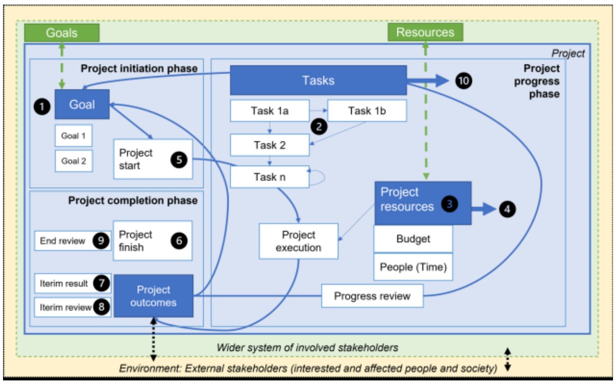

Figure 1 Components and relations of project management

Another way of dividing the project in phases is via the subsystems by Abdel-Hamid [1]. He introduces four major subsystems for projects: (1) human resource management: hiring/transferring people, defining employee types; (2) software production: models development, error detection, and productivity; (3) control: report progress of the project; and (4) planning: estimate and revise both project resources and schedule. Combining these subsystems in a model, integrates all its functions of both the software development and management processes. It shows the interactions between resources and their influence on each other [1].

4.2 System Dynamics for Project Phases

Lyneis et al. [15] show some specific uses of system dynamics in the project life-cycle phases. In the initiation phase, managers can use it to plan and test the feasibility of the proposed schedule and budget, given the scope of the project and other strategic requirements, such as a process model and organization structure. Additionally, system dynamics provides a range of possible competitive bids as a competitor analysis, determines the impact of possible changes in external conditions in a risk analysis, and works out changes that minimize the consequences of these risks.

Then in the progress phase, system dynamics helps calculate the impact of project risks that actually happen together with suggesting changes that minimize these consequences.

Furthermore, it can determine the cost and schedule implications to manage changes coming from external factors.

Lastly, in the completion phase system dynamics can benchmark and evaluate the best practices by comparing projects solely on management actions. Moreover, it can enhance training and development of managers using simulation models of projects as a "flight simulator" to allow practice and learning [15].

4.3 Applications of System Dynamics in Projects

Then for the application of system dynamics to project management, we come to the case study collection. The useful papers that resulted from the backward literature search based on [16] are [26], [15], [5], [1], [11] and [7]. To find more suitable case studies a systematic literature search is conducted. The following keywords are used in databases like Scopus, Google Scholar and Scinapse: "system dynamics", project management, case study, IT or software. The exclusion criterion is 'simulation'. Some alternatives for 'IT' were "information technology" and "computer industry", but this did not lead to any other (relevant) papers. For 'case study', the alternative 'application' was used as well, but this did not make a difference either. The language was limited to English and for some searches the subject area was limited to Computer Science; Business, Management and Accounting; and Social Sciences. These search queries resulted in the collection of the following papers: [6], [13], [14], [4], [9], [10], [28], [12], [22], [17], [2] and [24].

During the case study collection we decided to widen the scope to the use of project management in general, and not necessarily related to IT. As Table 1 shows, there are only four cases that fit in the software industry as an IT project. Case studies thus only have to apply system dynamics to (project) management to be included in this research. Cases that investigate the management of business units or companies in general are included as well, as long as it can also be applicable to projects.

From this literature review, we can already conclude that system dynamics is beneficial for projects, as demonstrated for example by the first case study (Section 5.2.1). It is highly relevant to support IT projects with a modelling approach like system dynamics because proper project management is essential. A bigger picture with all the links and loops of a project supports management decisions and can as a result significantly reduce the costs, issues, and time span.

5 RESULTS

5.1 Applications of System Dynamics

Table 1 gives an overview of the applications of system dynamics in project management. The indicated industries are software, construction, energy and electronics, transport, and miscellaneous for projects that do not fit in a category. The year represents the publishing date, so this might differ from the year in which the project was executed. It does show that using system dynamics for project management started years ago and is nowadays still relevant. The column 'Main goals' shows for each project what the main purpose was of the use of system dynamics. In Section 5.2 follows a summary for each of the projects and an explanation on why the projects are categorized in the corresponding phases and subsystems.

5.2 Uses of System Dynamics in Selected Projects

The following sections provide the summaries for 18 case studies that use system dynamics for project management.

5.2.1 Peace Shield Weapon System

The first case study involved the Peace Shield Weapon System on behalf of the Kingdom of Saudi Arabia [15]. The 54-month project considered the design, development, and testing, involving both hardware and software, of ground-air defence systems to the Saudi Air Force. The first part of the model for this project was based on the rework cycle, which incorporates the feedback effects on productivity and work quality, including knock-on effects. A simulation formed the base for risk assessment, that helped test the cost and schedule impact of assumptions on the liftability[1] of code, availability of staff, vendor delays, etc. During the ongoing project, the model was updated with novel information on performance and external conditions. This helped management of important decisions, like the implementation of a teaming structure instead of the normally used waterfall approach, which showed in the model that the project would finish 3 to 18 weeks earlier than planned. Another critical decision was the change in staffing strategy for software coding and engineering. Extra staff at the end of a project phase should work on undiscovered rework, even though that possibly delays the start of the next phase. These changes reduce program staffing by 20% according to the model. The result of the project was that it finished after 47 months, way before the planned 54 – and even expected 116 months. So, the program was deemed highly successful [15].

For the project life-cycle phases, the Peace Shield Weapon System is categorized in the initiation and progress phase. The reasons for this decision are that they started monitoring the project from the start to simulate risk assessment and then continued updating the model. This allowed management to take key decisions on teaming structure and undiscovered rework. For the major subsystems, the decision is to classify the use of system dynamics under planning, because it was used to estimate and revise the schedule. The other system is human resource management as the staffing strategy and project management style were changed based on the model.

5.2.2 NASA

Abdel-Hamid [1] discusses a post-project case study conducted at NASA. The project looked at the design, implementation, and testing of software that would process data and provide control to two different satellites. Because of this difference, they had to work with two sets of requirements for two software support systems. As "schedule maintenance is often considered the most important criterion for project management effectiveness" ([1], p. 161), the case study researched schedule compression in a multi-project environment. It shows that when compressing the schedule of project A, project B will increase in terms of costs and schedule. Something that is often overlooked. To meet a tighter schedule, a higher work force level is required, and project B must lend some of their staff to project A, resulting in an extended schedule. The second part of the case study investigates the impact of workforce allocation strategies on project behaviour. Examples of variables are the degree of overlap between projects and the average resource factor[2]. Some issues with this case study, according to Rodrigues [20], are that they do not consider project work breakdown and thus also leave out natural changes in the work intensity, and they consider stable requirements, which is something very unlikely in most software projects.

[1] Part of code that does not require change.

[2] Average resource requirement during a set period of time divided by resource availability.

Table 1 Applications of system dynamics

Industry	**Case**	**Paper**	**Year**	**Project life-cycle**	**Major subsystems**	**Main goals**
Software	Peace Shield Weapon System	[15]	2001	Initiation Progress	Planning HRM	Management policies
	NASA	[1]	1993	Completion (post-project)	Planning HRM	Inter-project management policies
	Hughes Aircraft Company	[5]	2002	Completion (post-project)	HRM Software production Control	Management policies
	On-demand enterprise software	[6]	2012	Completion (post-project)	HRM Software production Control	Adding personnel
Construction	Apartment blocks	[14]	2002	Progress	Control	Monitor and evaluate project dynamics
	Surabaya City Government	[17]	2022	Initiation	Planning	Improve performance
	Carriageway Egypt	[13]	2018	Progress	HRM Planning	Improve performance
	University Colombia	[4]	2020	Progress	HRM	Improve performance
	Urban Rail Transit Line 9	[28]	2020	Progress	Control	Risk control
	University Construction	[9]	2011	Progress	Control	Risk and error control
Energy and electronics	Project Isolated (BP)	[11]	2006	Initiation	Planning	Schedule Equipment
	Iranian IPP	[10]	2019	Progress	Planning Control	Management policies
	Mexican SME electronics	[24]	2017	Progress	HRM Control	Quality control
Transport	Toyota	[7]	2003	Progress	N.A.	Management policies
	Halter vs. Hess	[26]	1990	Progress	Control	Dispute resolution
	PSScycle	[12]	2015	Completion (post-project) Initiation	Planning	Monitor and evaluate project dynamics
Miscellaneous	Interpolis Stichting Rechtsbijstand	[2]	2005	Initiation Progress	HRM	Improve performance Management policies
	R&D market leader	[22]	2006	Progress	HRM Control	HRM policy

The conclusion after using a system dynamics model is that inter-project management policies are important. “They influence project behaviour in real and measurable ways, and in turn, project cost and schedule performance” ([1], p. 164). The system dynamics is applied in the project-life cycle phase of completion, since the case is a post-project analysis reviewing the process of the project and the consequences of decisions. Because the system dynamics model looked at project cost, schedule, and staffing, it is categorized in the planning and human resource management subsystems.

5.2.3 Hughes Aircraft Company

Hughes Aircraft Company is the same company that handled the Peace Shield Weapon System project. Cooper et al. [5] discuss another program that took place before the Peace Shield program, but it was a lot less successful. The project life-cycle phase for this project is categorized under project completion, as a post-project analysis was performed for learning purposes. In this analysis, researchers compared the Peace Shield program to the past program by removing all differences in scope and external conditions. After doing so, there was still a halving of cost and time for the Peace Shield project, which was a result of managerial differences. After making changes to the past program that were in line with the Peace Shield policies, the past program was successful as well [5]. The use of system dynamics is grouped under human resource management, software production and control for the major subsystems. This decision is based on the facts that first a whole new training system for managers was developed based on this past learning. Second, software enhancements like a web-based interface and new software tools for managers made the learning systems more effective. Third, there was differentiation between the actual and perceived model variables, making the system dynamics use part of the control subsystem.

5.2.4 On-demand enterprise software applications

Farshchi et al. [6] researched the impacts of adding new workforce to medium-sized, in-house, new development projects of a well-known company in the software industry. It is a post-project analysis, so the corresponding project life-cycle phase is the completion phase. The project that was analysed was planned to finish in 375 days, but after 200 days they were 35 days behind schedule. The model showed that when 6 people were added without considering their skills, the project would complete on day 434. In fact, it finished after 439 days. However, if the company had considered their personnel factors, the project would have finished after 406 days. Comparisons with the actual project showed that when skills of staff are considered, the prediction achieves better accuracy. The major subsystems are human resource management because it affects hiring of people; software production as the model looks at productivity; and control, since the researchers compared the actual versus the simulated simulation.

5.2.5 Apartment blocks in Australia

This project in the construction industry concerns two six-storey apartment blocks in Australia. The system dynamics research [14] looked at the project management dynamics of the project and found out that quite some information within the contract documents was inaccurate, identified rework was a result of poor skills and personnel planning, and 50% of the rework was the result of poor motivation levels of staff. The model showed the causal relations between these factors and gave an overview of the forecasted versus actual costs. The result of the research was that “the dynamics of a project system should be monitored and evaluated by project managers” ([14], p. 434). This would have to be done according to the following functions: planning (managing complexity), organizing (allocate tasks to people and request resources), commanding (leading, communicating and cooperating), and controlling (set contingencies and control the release of the project). The project has been monitored from the start, but as the model was based on events happening throughout the project, it is categorized in the progress phase. The major subsystem that is chosen for this project is control. The model showed that managers should monitor and evaluate the project better, compared to the poor start with inaccurate documents and bad skills, which resulted in higher costs [14].

5.2.6 Surabaya City Government

The Surabaya City Government generally runs infrastructure projects with a limited duration of one year [17]. The goal was to improve performance, so the budget absorption could be maximized. System dynamics was therefore used to determine what the impact of project duration acceleration would be on contractor’s profits and contingency costs. This would directly affect the budgeting and planning processes. The system dynamics model found that when contractors improve performance by accelerating the project duration, the profit would increase between 1.05% and 4.72% because of reduced indirect costs, and the schedule performance index would increase from 1 to 1.06. The project life-cycle phase in which system dynamics is used is thus the initiation phase, because it is related to planning: what is the impact of project duration acceleration on planning processes. This is therefore also the chosen major subsystem.

5.2.7 Carriageway Egypt

The project discussed by Leon et al. [13] had as goal to improve and widen a single carriageway in a dual asphalt road in Egypt. The planned duration of the project was 16 months and the researchers collected data after 9 months when the finishing time was the primary concern. The researchers created four models, one as baseline and the other three with potential improvements. The first simulation got implemented to achieve a timely completion: the implementation of an incentive program for project staff and labour. As a result, the simulated final performance came remarkably close to the actual project values and the increased team satisfaction positively influenced productivity. This led to a decrease from 16.81 to 16.07 months, resulting in just a small delay. The project life-cycle phase that fits this project is thus the progress phase, since the model was used during the execution of the project. The subsystems for which system dynamics was used are human resource management as a new program was introduced; and planning, because the model helped revise the project schedule.

5.2.8 University Colombia

Cano and Rubiano [4] researched the situation of a university in Colombia that runs several infrastructure projects. The simulated model of 2.5 years was first verified so that it was consistent with the actual situation of the management process. Based on this model, a future state map was then created with the most suitable scenario in terms of performance indicators. This included the approval of investment, where a cash transfer mechanism would allow resources to be available, and the own and supplementary administrative processes, which identified most of the waste management processes. The conclusion was that applying Lean tools would help achieve the economical use of personnel and build a culture of waste disposal. Symptoms of problems in the value flow should be analysed systematically to get to the root of problems and consequences. Another recommendation for the university was to define a process for the selection of designers and consultants, so they could contribute to achieve high standards of design constructability. The project life-cycle phase can therefore be determined as the progress phase, because the model was made after 2.5 years of projects. For the major subsystems, the use of system dynamics is categorized as human resource management, because of the recommendation on the hiring process to select new employees.

5.2.9 Urban Rail Transit Line 9

The urban rail transit Line 9 project in Shenzhen was a construction project of 48 months [28]. The goal of the system dynamics use was to simulate safety risks in a dynamic way. For the research, 741 risks were extracted and grouped into five categories (investigational, design, technological, managerial, environmental) that interact with each other through causal relationships. The model was used to predict the safety risk level, indicating when it was low or high. In case it was high, managers would get a warning that an accident might occur. The analysis also provided an overview of the ten most sensitive safety risk factors, providing strong risk control measures to weaken these factors. The system dynamics model was thus used in the progress phase of the project life-cycle. The major subsystem that is chosen for this project is the control system, because the risk factor overview serves as an aid to keep control over the project. This is an excellent demonstration for the literature on monitoring risks [15].

5.2.10 University construction

For this project, system dynamics was used to model the impact of design errors on project performance during the construction of a new university building [9]. The schedule was 24 months and the completion date was set in May 2008. In November 2007, the current progress was analysed, and it resulted that design errors lead to schedule delays. The simulation model showed that even with consideration of hidden design errors and additional risks, the project would complete in November 2008, too late for the new university season. However, the project would be far enough by August, so the building could partially open for the new year. The model aided construction managers with assessing the negative impact of design errors in a more systematic way. It recognised that causes and effects of committing errors are not just linear, but instead are looped in their relationships. System dynamics is used during the progress phase of the project, since the project started a few months before the model was made. For the major subsystem, the control system is chosen, because the model helps to monitor the impact of design errors and therefore gain control over the project.

5.2.11 Project Isolated (BP)

The case study of the Project Isolated case is a situation encountered by a BP project team [11]. The issue was that the team needed a specialized piece of equipment for a remote location. Normally, the transport would be via sealift, but the time window for delivery is small and missing it leads to a delay of several months. Another option is the use of an airlift, but this costs $500.000. The transportation window with the sealift lies between week 25 and week 30. The system dynamics model showed that before week 25 the airlift would not be valuable, but after week 25 it can increase the expected project value by 5-6 million. This was also the decision by the manager, who concluded that the airlift reduced the risk of project delay and added value to the project. The project life-cycle phase for this project is categorized as initiation and planning. The model helps estimate the planning of schedule and equipment, classifying it as the planning subsystem.

5.2.12 Iranian IPP

The case study on the Iranian IPP concerns the project portfolio management policies of a private independent power producer (IPP) [10]. The company has projects in four strategic business units and their current strategy is an investment program that pushes the company's cash flow to a negative value, thus leading to bankruptcy. The consultancy project created a system dynamics model to simulate the current base run and a newly proposed policy by the management team. In this policy, there is less investment initiation, which solves the cash flow problem. It shows the company how it can optimally use its resources and thus be more successful in the future. Some scenarios that this industry must consider are the effects of project portfolio dynamics: short-term success should not lead to disregard of long-term success; balanced allocation of resources is a key factor for investment; simulating managerial decisions can help understanding and teach new mechanisms; and investment portfolio prioritization can be frequently revised as it is a dynamic process. The consultancy project used system dynamics in the progress phase of the project life-cycle, to determine how the company would continue in the future without going bankrupt. This can also be useful for projects instead of companies, as these also deal with limited funds. For the major subsystems, it is categorized under planning: how to deal with resources and the execution of activities, and under control: what are the differences between the actual and modelled situation.

5.2.13 Mexican SME Electronics

The case study by Vallejo [24] concerns a Mexican SME[3] in the electronics manufacturing. The main purpose of the project was to reduce operating costs, eliminate product rejects and fulfil customer orders. The system dynamics model showed that the key issues were quality problems and poor equipment effectiveness, machine reliability, and a lack of skills for operators. A new training program was created to develop new and enhance existing skills. The introduction of an autonomous maintenance program decreased major maintenance activities and machine repairs, increasing the output, reducing working hours for rework, and improving labour productivity. The category for the project life-cycle is the progress phase because the project used system dynamics for the execution strategy of the company. Because the model looked at a training program for employees and a maintenance program, the selected subsystems are human resource management and control.

5.2.14 Toyota

The case described by Ford and Sobek [7] concerns the development processes and management of Toyota. It simulates flows and accumulations of development work for four alternative automobile system designs through three development phases. It is related to the Second Toyota Paradox, which is the consideration that Toyota out-performs its competitors with the fastest development times and high profitability, while they delay key decisions. The model compared two development paradigms: point-based (where a single alternative is selected early in the development) versus set-based (where multiple alternatives are compared and reduced to one just before the project finishes). The model showed that the set-based project values are higher than point-based project values. As soon as the quality benefit of delaying managerial decisions has been obtained, the maximum project value is reached. Keeping more alternatives alive beyond this

[3] Small-to-medium sized enterprise

point will increase development costs without adding value. The category for the project life-cycle is thus the progress phase, as it is used to construct the deliverables of Toyota in terms of the alternative automobile system designs. It gives insights for other design projects on the different strategies and shows that a set-based paradigm may be more beneficial than initially expected. For the major subsystems, none is applicable for this case study.

5.2.15 Halter versus Hess
Weil and Etherton [26] describe the use of system dynamics in dispute resolution. This dispute was between Halter Marine and Amerada Hess Corporation, which is an oil empire. The ongoing project between the companies had as aim to build ocean-going vessels to transport oil and other related products. After their disagreements started, Halter filed a lawsuit seeking damages of 60 million dollars, because in their opinion Hess did not live up to their obligations and changed too much in the plans. These changes were of such magnitude that Halter could not reasonably anticipate. Hess however argued that Halter's problems came from incompetency, poor management, bad planning, and scheduling. Halter thus had to quantify the damages and created a simulation system dynamics model as a base, that showed the actual history of the project. Another simulation showed what would have occurred if Hess had not made changes to the plans and delayed the progress by their other actions. The model was found to be valid and Halter received a favourable settlement. The project life-cycle phase in which system dynamics is used in this project is the progress phase, as the project had already started. The major subsystem is the control system, because the progress of the project is reported and there is differentiation between the actual and perceived model variables: it investigated what the difference was between the actual course of the project and simulated version without trouble caused by Hess.

5.2.16 PSScycle
PSScycle was a project that developed an innovative e-bike sharing system [12]. The use of system dynamics for this project is of descriptive nature in a post-project analysis. The corresponding project life-cycle phase is therefore the completion phase. The goal of the simulation model was to give insight into underlying dynamics of the development process, give decision support, and support benchmarking of process sequences. The simulation of the project resulted in a duration of 106 days, while the plan was to finish in 100 days and the actual duration was 105 days. Especially the tasks for hardware component development made the overall duration increase, causing additional rework. As optimization possibilities, reducing the error rate of function tasks or accelerating the hardware tasks were identified. As mentioned, this analysis is categorized in the completion phase. The conclusion by the researchers, however, is that it ideally can be used in the early phase of the engineering design process, "to give insights into the potential future behaviour of the system" ([12], p. 507). The matching major subsystem is the system of planning since the conclusion was to accelerate tasks.

5.2.17 Interpolis Stichting Rechtsbijstand
The use of system dynamics discussed by Akkermans and van Oorschot [2] concerns the management of a business unit of Interpolis (Stichting Rechtsbijstand) rather than a project. The case study investigated productivity, cost-effectiveness, customer satisfaction and pressure-motivation loops. There were three optional managerial policies to increase performance. The first policy outsources more cases to external companies to relieve workloads, the second policy is a training program for new staff to boost their ability to handle higher workloads, and the third policy involves more experienced employees in the intake processes, as it would have a positive effect on work pressure and productivity. Based on the simulation outcomes, this third one was chosen. The model predicted that first the performance would deteriorate further, after which it would considerably improve in the second half of the year. This was also how the future unfolded. Because system dynamics was used on an existing business unit, it can be categorized as the progress phase of the project life-cycle. Another suitable category is the initiation phase, as the model is used to make a strategic decision regarding the intake processes of new employees, which can also be beneficial for projects. The related subsystem is thus human resource management.

5.2.18 R&D of a market leader
Snabe and Größler [22] describe the case of a major international company which is a market leader in its main product area. The company has a sustainable competitive advantage, for which their research and development (R&D) department is a big and important part. However, there are problems regarding the development of a balanced strategy and implementation plan for the number of R&D employees in high-cost countries, compared to low-cost countries. The objective of the system dynamics model is to understand the most influential parameters in building up capacity in low-cost locations and to define the ideal strategy. As a result, employees in high-cost locations would not be replaced in the first three years. Training time would be reduced, actual numbers underlying business cases needed to be aligned, and there would be a shift from headcount orientation towards cost orientation. Additionally, detailed transfer planning and the exchange of best practice experiences with other business units came out as important practices. This all resulted in valuable outcomes on individual, group, and organizational level. The use of system dynamics is categorized in the progress phase, as the model is created for an existing business unit, but projects can also benefit from for example the exchange of best practices. For the major subsystems, it is classified under human resource management and control, because it involves employees and also looks at numbers regarding costs of locations and best practices from other business units.

6 CONCLUSIONS AND DISCUSSION
For the conclusions we first return to the sub-research questions. The first research question concerns in which project phases (initiation, progress, completion) system dynamics is used and whether it turned out to be useful. For twelve of the analysed projects it was used successfully in the progress phase, five projects used system dynamics in the initiation phase and four used it in the completion phase. For these last four projects it was a post-project analysis with a learning goal, so none used it to actually wind up the project. An interesting observation is that two of these projects (NASA and Hughes Aircraft Company) used system dynamics to get insights on management policies, while for example the Peace Shield project demonstrates that using system dynamics in the initiation phase for this same purpose is highly valuable. These insights show that system dynamics is not only used for operational project management, but also for strategic purposes.

The case by Hughes Aircraft Company [5] shows that the use of system dynamics in the completion phase of a project is beneficial for learning purposes, as they created a whole new training program for managers based on the outcome of the model. Next to the Peace Shield project, another interesting lesson for the initiation and planning phase comes from the Surabaya City Government case [17]. It gives the insight that accelerating the project duration results in an increase in profit and schedule performance index. Or, like the Project Isolated case [11] demonstrates, system dynamics can help with the planning around equipment. For the progress phase some interesting projects are the Urban Rail Transit Line and the Mexican SME Electronics. The Urban Rail project [28] shows how useful system dynamics is when it comes to risk management, giving an overview of risks and how to mitigate them. The Mexican SME project [24] demonstrates how system dynamics can give insights in key issues happening in a company, regarding skills of staff and quality issues.

The second research question covers for which of the major subsystems (HRM, software production, control, planning) system dynamics is applied. Nine projects used system dynamics for human resource management, only two used it for software production, nine projects used system dynamics in the control subsystem, and seven used it for planning purposes. The lack of software production can be explained by the fact that there were only a few software-related projects reported in literature. If we look at the goals of these projects (Table 1), the focus was often on HRM. Within the industries there is not a specific subsystem that is used more often than the others, but there is a link between the main goals (Table 1) and the corresponding subsystems. For example risk, error, and quality control are categorised in the control subsystem, and a main goal that is related to schedule management belongs to the planning subsystem.

A lesson learned for human resource management is that system dynamics is of great help when creating new management programs. The Carriageway project in Egypt [13] shows this with improved performance as a result of the incentive program, the Mexican SME [24] created a successful training program, and Interpolis [2] developed a new policy for the intake processes based on a system dynamics simulation. These new programs that were created because of system dynamics also support new projects before they even start. In the control subsystem one of the most important benefits is risk management, as demonstrated by the Urban Rail [28] and University Construction [9] projects. Another interesting case was the one of Halter [26], which showed that system dynamics can aid in winning a lawsuit.

The case study by Farshchi [6] on adding personnel shows that software production is positively influenced when considering people’s skills, as a take-away for the software production subsystem. As mentioned in the introduction, one of the biggest issues in software project management is that human factors are not incorporated [20], so this case provides interesting evidence. The same lessons of the initiation phase based on the Surabaya City Government [17] and Project Isolated [11] apply to the planning subsystem. System dynamics is thus useful for operational day-to-day tasks such as shifting personnel between projects and creating a planning around available resources.

The third research question explores which industries benefit from the use of system dynamics for project management. The industry that came forward most times in this research is the construction industry with six cases. For the software industry there were four projects found. Both ‘energy and electronics’ and transport were represented in three case studies, and two projects were categorized as miscellaneous. The successful applications in the construction industry show that it is beneficial for this industry to use system dynamics. Most of the projects used it to improve their performance or to monitor risks. Both are important aspects for this industry, as shown by Albtoush and Dho [3] who rank time, cost, and quality as the top-three key factors affecting construction performance. For the other industries, most of the applications have different goals, so the conclusion is that within an industry there are many possibilities to use system dynamics. It is of great importance because of its wide range of uses and benefits. Whether it is a project that has interrelations regarding sharing of resources, or a standalone project or business unit, everything can profit from the modelling approach.

To answer the main research question “*What are the applications of system dynamics in project management?”* we return to Table 1 and Section 5.2. As portrayed there, the range of applications is rather broad, because the case studies show that it can benefit both projects and companies in different project phases and subsystems. The conclusion – and the practical contribution of this research – is therefore that companies can use system dynamics for all sorts of projects. The best strategy is to use the modelling approach in the initiation or progress phase, and possibly as an addition in the completion phase. This brings the best benefit, because project managers can immediately apply the recommendations by the model. As shown by the most often reoccurring main goals, system dynamics for example helps to improve (project) performance and to test existing or new management policies. We can also conclude that the applications of system dynamics in IT project management are still limited. However, the reviewed case studies show that software projects can profit greatly from the use of system dynamics. Additionally, the projects from other industries show applications that can also be valuable for software projects despite their differences in scope.

7 RECOMMENDATIONS AND FUTURE WORK

To follow up on the post-project analysis applications of system dynamics for IT project management, the recommendation for these projects is to use system dynamics earlier. The post-project analyses and other case studies show that system dynamics is useful, so if these companies were to use it for their projects in the initiation and/or progress phase it would be more beneficial. To additionally use it in the completion phase to wind up the project or for learning purposes can add an extra benefit.

As touched upon in the answer to the main research question, there is only limited documentation on the use of system dynamics in IT project management. Even though literature has shown that it is beneficial for IT projects, in reality there is a gap between this literature and applications. The academic contribution of this research is thus a recommendation based on the identified gap: researchers and companies should start using system dynamics for IT project management, and document the applications. As all life-cycle phases and all subsystems were present for this industry, there are numerous possibilities. Other industries also show a wide range of applications, providing more learning material for IT projects. As Lyneis and Ford [16] concluded as well, publication of more success stories will improve the adaptation of system dynamics in the project management field. There are many more (successful) applications than discussed in literature. This lack of documentation makes it difficult to spread and reach managers who can benefit from the modelling approach.

For further research, a recommendation would be to reach out to companies that apply system dynamics to their projects. This will help create a better overview of system dynamics applications, because only a small part of it is documented in literature. With the timespan of this research it was not possible to pursue this, but for future work it is interesting to investigate.

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