Master's Thesis

Industrial Engineering and Management

Improving BearingPoint Netherlands' consultant-to-project KPIs by introducing a consultant-to-project assignment model

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MANAGEMENT SUMMARY

This research is performed at BearingPoint Netherlands (BE NL) in Amsterdam. BE NL is part of BearingPoint (BE). BE is an independent multinational management and technology consulting firm and offers three types of services, which are consulting, products, and capital. BE NL only has the Consulting service and is active in People & Strategy (P&S), Customer & Growth (C&G), Data & Analytics (D&A), and Technology (TECH). Consulting is a professional service provided by firms to offer specialized advice and solutions to individuals or organizations, addressing specific challenges or improving performance. These challenges or performance improvements are referred to as projects and can run from 1 week until multiple years. The consultancy firm has to match consultants to these projects with respect to required skill set and consultant satisfaction and that is a difficult decision. We call this the Consultant-To-Project assignment(s) (C2Pa) procedure. The Operational Team Lead (OTL) team makes the C2Pa and the stakeholders for the C2Pa procedure are the consultants of BE NL, BE NL itself (due to its financial dependence on the C2Pa), and their clients. The OTL team currently bases their staffing decision on common sense and does not involve any computational intelligence like for example assignment cost, consultant utilization, or consultant satisfaction. Since the OTL team bases their C2Pa decisions on common sense, the C2Pa procedure is unstructured and ambiguous.

The unstructured and ambiguous C2Pa procedure hinders the OTL (team) with effectively managing the resource allocation, consultant satisfaction, project quality, and consultant assignment cost, resulting in suboptimal C2Pa that a) fail to balance the needs of all stakeholders involved, b) lack transparancy and visibility, c) are subjective & biased, d) are time intense, and e) lack long-term planning. The reason why BE NL currently has an unstructured and ambiguous C2Pa procedure is threefold. First, there are no clear measurable performance KPIs. Second, the input data is incomplete or absent. Third, the decision-making in the C2Pa problem has many stakeholders, is ever changing, and has a subjective element, making the decision-making very complex. Improving BE NL's C2Pa procedure is important since the C2Pa procedure is a crucial and multifaceted element in the consultancy, playing an important role in the effectiveness and success of client engagements, consultant satisfaction, and the financial performance. Therefore, the main research question is:

"How can BearingPoint Netherlands create a C2Pa model that helps improving the C2Pa procedure by making the C2Pa procedure structured and unambiguous?"

According to literature, the C2Pa application area deals with methods to match consultants to projects in a way that maximizes the project's success probability while also ensuring client and consultant satisfaction. The C2Pa application area does not have a standard problem base and solution for solving the C2Pa problem. The simultaneous multi-project scheduling and multi-skill staffing problem of Heimerl and Kolisch (2010a) is the most suitable base for modelling the C2Pa problem (Section 3.2). However, the model of Heimerl and Kolisch (2010a) required significant adaptions in constraints and objectives to be able to solve the C2Pa problem. We made the single-objective model of Heimerl and Kolisch (2010a) multi-objective by implementing the revised Multi-Choice Goal Programming (MCGP) of Chang (2008). Next to the hourly cost of assigned consultant KPI which is based on the cost KPI on the model of Heimerl and Kolisch (2010a), we also added the consultant-to-project utilization KPI based on the efficiency of the workforce KPI of Zabihi et al. (2019), consultant satisfaction KPI based on the salesmen satisfaction KPI of Abboud et al. (1998), and the C2Pa skill match KPI on the quality KPI of Chen et al. (2020). The C2Pa model maximizes the consultant-to-project utilization KPI, minimizes the hourly cost of assigned consultants, maximizes the consultant satisfaction KPI, and brings the C2Pa skill match KPI as close to zero as possible. Furthermore, the C2Pa model declines projects in case accepting the project leads to an infeasible solution.

With the C2Pa model we provide the following insights:

- Performance evaluation of the current procedure versus the C2Pa model: By comparing the outcome of the C2Pa model with the outcome of the current procedure, we can check the solution quality of the C2Pa model. This evaluation helps assessing the overall effectiveness of the C2Pa model.
- Impact of flexibility in the project start time window sizes: By varying the start time windows we can investigate the impact of the start time windows on the solution. These insights are valuable for companies to determine if they want to negotiate more with their clients about the starting times of projects.
- Useability C2Pa model with respect to company (problem) size: By increasing the number of projects and consultants we provide insights in the usability of the C2Pa model for different company sizes with respect to performance as well as computational times.
- Effect organizational capabilities: By using different consultant skill sets, we can see the impact of companies with better and worse skilled people on the solution. Furthermore, varying the organizational capabilities illustrates how training your employees on skills influences the solution.

In the benchmark between the OTL assignments and the C2Pa model assignments, we observe that the C2Pa model outperforms the OTL assignments by improving 2 KPIs (decreasing the average hourly cost with 4.19% and increasing the satisfaction with 5.95%) and keeping one KPI the same (utilisation since the same projects are assigned). The C2Pa model compromises on the C2Pa skill match KPI by making the assignments slightly more underqualified (-1). Moreover, the C2Pa model's computation time is 0.99 seconds. Notice that due to the time intensiveness of creating the OTL benchmark instance we were only able to perform the benchmark on a small instance (creating the assignments for the OTL scenario costs a lot of time for the OTL team).

The flexibile project start time windows experiment showed that increasing the time window sizes decreases the number of declined projects, increases the consultant to project utilization, increases the average hourly cost, decreases the skill match, and an increase in satisfaction for a start time window size of 2 and 3 weeks.

The company size experiment showed that increasing the company size decreass the number of declined projects, increases the utilisation, increases the average hourly cost, increase the consultant satisfaction, and decreases the skill match (with exception for the smaller company size scenario). Furthermore, we observed an exponential trend between the company (problem) size and the computational times. For large companies, the C2Pa model in current form therefore becomes problematic.

The organization capabilities experiment showed that increasing the organizational capabilities has no effect on the number of declined projects, has no effect on the consultant to project utilisation, has no relationship with the satisfaction, increases the skill match, and decreases the average hourly cost. Moreover, based on these instances even a sweet spot for the C2Pa skill match KPI was found (skill match KPI equals 0). The sweet spot is reached between an average consultant skill level increase between 0.5 and 1.

Based on the experimental results and insights of the research, we are able to formulate the following recommendations:

- C2Pa model implementation and integration: The C2Pa model is proven to be succesful in solving the issues with the current C2Pa procedure. We therefore recommend BE NL to implement the C2Pa model in the C2Pa procedure as decision-support tool.
- Improving the availability of input data: To ease the process of transforming project information to project characteristics needed for the C2Pa model, we recommend to create a prompt for generative AI like Bing Copilot or ChatGPT. This enables the user to copy and paste the project description together with the prompt in the generative AI and automatically receive the skill levels for the required project skills as output. However, make sure to use a generative AI that is in line with the company's policy and the GDPR.
- C2Pa model input extension: Currently the C2Pa model only focuses on the D&A service line. However, since the issues of the current C2Pa procedure are experienced in every service line it is recommended to extend the model to all service lines. In this way, the C2Pa model can do the assignments for BE NL as a whole. Extending the C2Pa model for all service lines can easily be done by extending the input data.

PREFACE

Dear reader,

You are about the read my master thesis “Improving BearingPoint Netherlands’ consultant-to-project KPIs by introducing a consultant-to-project assignment model”. This research is executed at BearingPoint Netherlands in Amsterdam as final assignment for my master Industrial Engineering and Management (IEM) at the University of Twente.

At Bearingpoint Netherlands (BE NL), I have gained a lot of new insights and experiences, participated in team events and trainings, met a lot of inspiring people, and made new friends. I am grateful for this opportunity. I want to thank everyone who was involved in this research for their willingness to help and their massive support. Without the expertise and help of everyone, I was not able to finish this master thesis.

A special thanks to my supervisors at BE NL: Joost Kuckartz, Joost van der Ploeg, and Tristan Slobben. You really guided me during this research. I want to thank you for your trust, for always being available for my questions, your feedback, and the meetings which were always nice. On top of that, I really appreciated your flexibility and thoughtfulness. Also thanks to Yorick, Boaz, Rajen, and Stefan for all the nice buddy meetings and events we had together.

I would like to thank my university supervisors Marco Schutten and Eduardo Lalla as well. Both always found time available to discuss my thesis. With their extensive and critical feedback, I was able to improve my thesis. So thanks a lot!

My study time in Enschede already came to an end in February 2023, when I moved to Heerhugowaard to perform my master thesis at BE NL in Amsterdam. I want to thank my girlfriend, family, friends, and old housemates for their continuous support. You supported me to all ups and downs that came with this research and encouraged me to make the most out of it. Your support was not only there during this research, but also during my entire study period so many thanks for that! I really enjoyed my five years of studying at the University of Twente and I am looking forward to the future, with all its opportunities and challenges.

I hope you, as a reader, enjoy reading my master thesis!

Bram Zentveld

Heerhugowaard, January 2024

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LIST OF ACRONYMS

BE BearingPoint

BE NL BearingPoint Netherlands

C2Pa Consultant-To-Project assignment(s)

EM Engagement Manager

MCGP Multi-Choice Goal Programming

MILP Mixed-Integer Linear Programming

OTL Operational Team Lead

RCPSP Resource-Constrained Project Scheduling Problem

CONTENTS

1 INTRODUCTION

The research we describe in this master thesis is a graduation assignment conducted at BearingPoint Netherlands (BE NL) for the master Industrial Engineering and Management (IEM) at the University of Twente. BE NL is a consultancy company and the research is about the assignment of consultants to projects. The Consultant-To-Project assignment(s) (C2Pa) procedure at BE NL is currently unstructured and ambiguous leading to suboptimal assignments. This research solves this problem by introducing a C2Pa model. Section 1.1 gives a short summary about BearingPoint's history as well as their services. Section 1.2 describes the reason for this research. Section 1.3 gives the problem statement of the action problem that followed from the research motivation. Section 1.4 describes the research goal. and the research questions. Section 1.5 describes the research design by elaborating on the approach and methods used for answering the research questions.

1.1 About BearingPoint

BearingPoint (BE) is an independent multinational management and technology consulting firm. BearingPoint offers three types of services, which are consulting, products, and capital. In 2021, BearingPoint employed 4261 people over 41 practices (offices) in 23 countries (BearingPoint, 2021). BearingPoint's roots go back over 100 years ago. At that time, two big names existed in professional services: KPMG and Arthur Andersen. In 2000, KPMG spun off some of its consulting units and began a rapid global expansion – acquiring a majority of Arthur Andersen's business practices. In 2002, the company changed its name to BearingPoint Inc. and so BearingPoint started. The rapid growth continued but eventually led to financial difficulties and bankruptcy in 2009. This challenging situation created an opportunity for BearingPoint's European leaders. They seized the opportunity and executed a management buyout, making the independent BearingPoint partnership they are today (BearingPoint, 2019). Figure 1.1 visualizes the locations of BE's offices as well as some key numbers of BE.

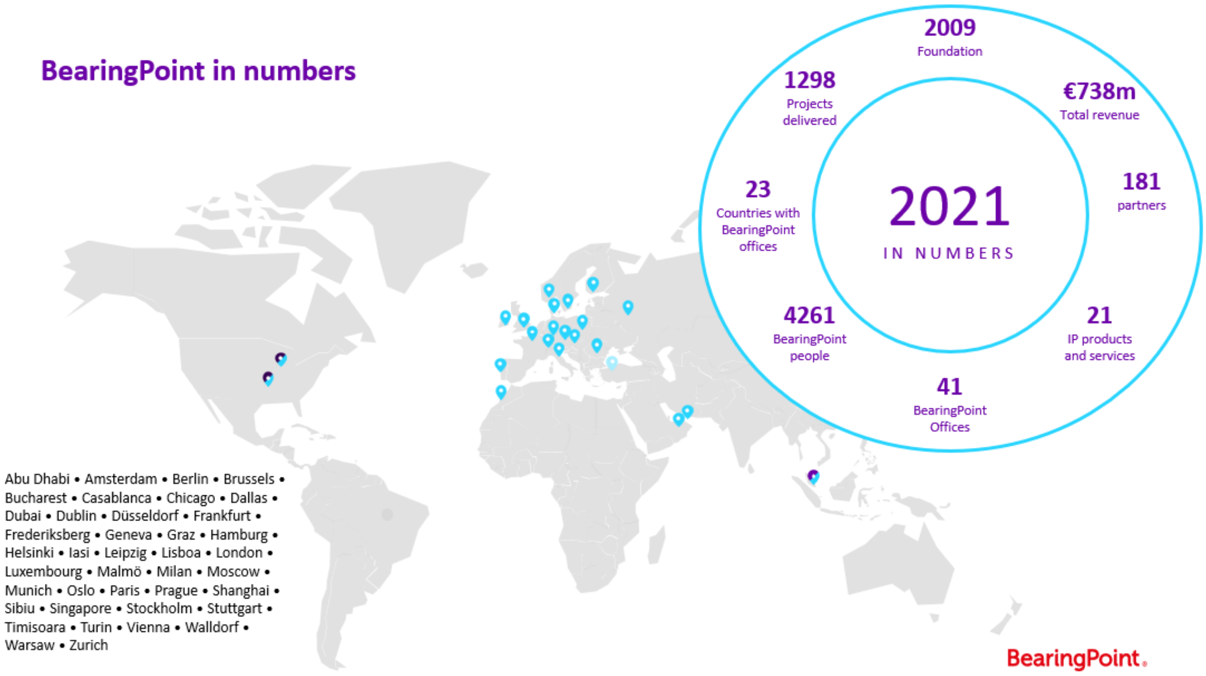

Figure 1.1: BearingPoint in numbers (BearingPoint, 2022)

BE NL only has the Consulting service and is active in People & Strategy (P&S), Customer & Growth (C&G), Data & Analytics (D&A), and Technology (TECH). In January 2023, BE NL approximately employed 80 persons working in consultancy, finance, and human resource management. Figure 1.2 visualizes BE NL' service lines and some of BE NL' clients.

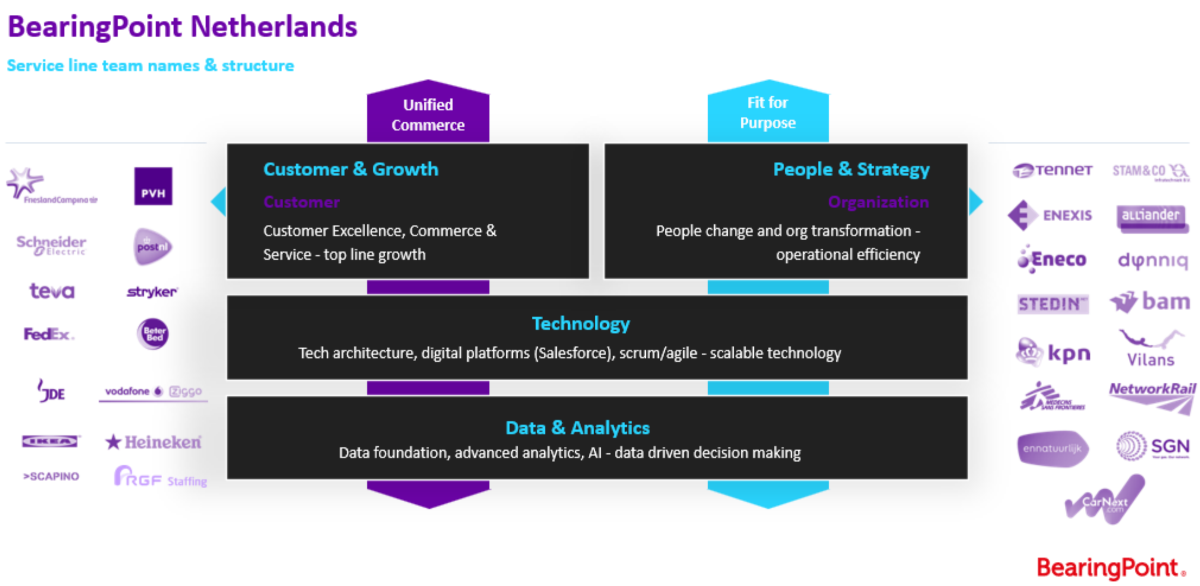

Figure 1.2: BearingPoint Netherlands company structure (BearingPoint, 2022)

1.2 Research motivation

The C2Pa procedure is a crucial and multifaceted element in consultancy, playing an important role in the effectiveness and success of client engagements, consultant satisfaction, and the financial performance. The C2Pa procedure involves strategically matching consultants with the right expertise, experience, job position, and skill sets to the specific projects.

From a financial perspective, the C2Pa procedure allows consultancy firms to optimize their resource allocation. By carefully considering the project's objectives and requirements, and the consultants' availability, BE NL can allocate the resources efficiently, making sure that consultants are utilized (cost) effectively and clients are satisfied. Simultaneously, the C2Pa procedure also takes into account the satisfaction and preferences of the consultants themselves. By considering factors such as personal interest, and professional growth opportunities, the consultancy firm can foster employee engagement and satisfaction. This approach helps attracting top talent to the consultancy firm, reducing turnover rates, and promoting a positive work environment. Balancing project profitability, resource utilization, the match between the project and the consultant, and the consultant satisfaction throughout the C2Pa procedure, therefore, contributes to the sustainability and financial viability of the consultancy firm making the C2Pa procedure a crucial element. Figure 1.3 shows a visualization of the C2Pa stakeholders and their needs.

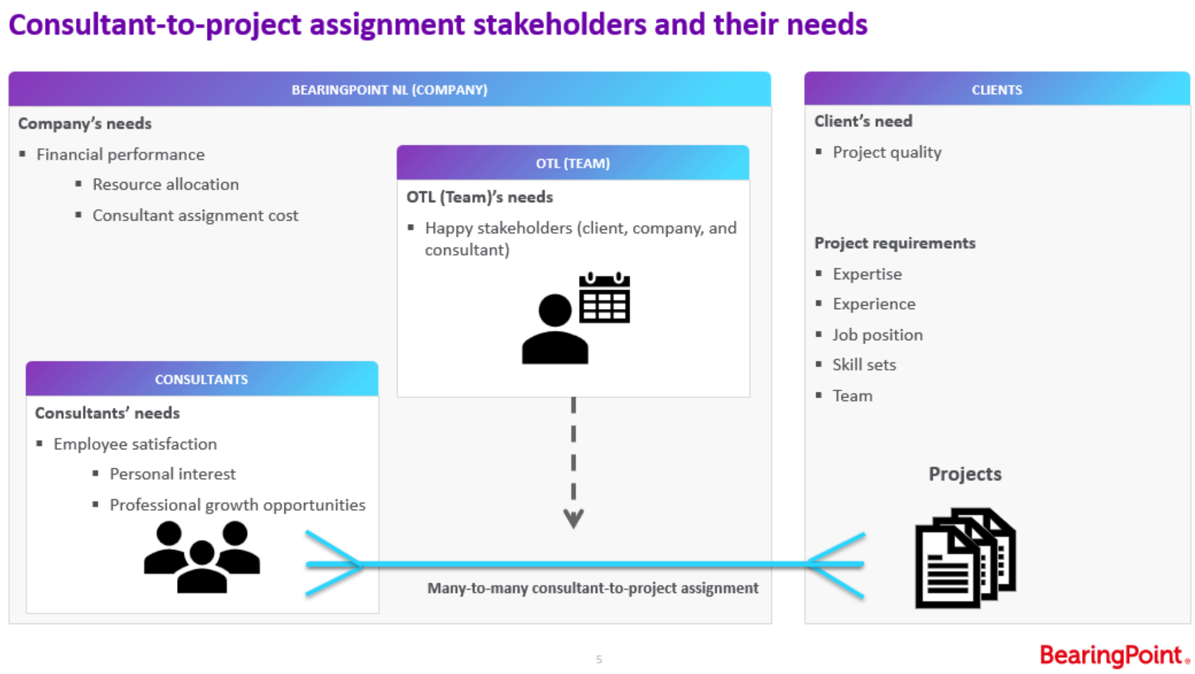

Figure 1.3: Visualization of the C2Pa stakeholders and their needs

The Operational Team Lead (OTL) team is responsible for the C2Pa and consists of five people, including one from HR and one for each service line. The OTL team bases their C2Pa decisions based on common sense and does not involve any computational intelligence like for example the cost of the assigned consultants. Since the OTL team bases the C2Pa decisions on common sense the C2Pa procedure is unstructured and ambiguous. Furthermore, the C2Pa procedure is only triggered when the need arises. This need arises when a new request for consultant(s) for a project comes in. The C2Pa procedure therefore happens ad hoc implying decisions on a case-by-case basis often based on immediate needs or based on the consultant's availability at a specific time. While an ad hoc procedure can offer adaptability and flexibility, an ad hoc procedure for BE NL also leads to inefficiency (time intense and suboptimal assignments), lack of visibility and transparancy, inconsistency (subjective & biased decisions), and a lack of long-term planning. Table 1.1 explains the reasons of the consequences of the current C2Pa procedure. The short description of the current C2Pa procedure at BE NL provided in this section is to illustrate the problem BE NL encounters. Section 2.3 provides the detailed description of the C2Pa procedure at BE NL.

Consequence	**Reason**
Suboptimal assignments	Since the OTL (team) performs the current C2Pa procedure manually and in an unstructured way, suboptimal assignments could be made. The OTL (team) could for example forget to include a consultant in the C2Pa decisions which had a very good match with the project, or the OTL (team) could unbalance the stakeholders by (consistently) favouring one group's interests over another's. For example, a client could desire a certain consultant for a specific project while this desired consultant could have a different personal interest. In this case, one of the stakeholders does not get their wish. This situation is inevitable, but it is important that the OTL (team) ensures that these compromises are equally spread over the stakeholders so the stakeholders' needs are balanced.
Lack of transparancy and visibility	The current C2Pa procedure does not have measurable KPIs to base the assignment decision on. Decision-making currently therefore only happens on common sense. The OTL (team) does not document this common sense making the past C2Pa opaque.
Subjective & biased	Since the decision-making only happens based on common sense, emotions of the OTL (team) and relations with the consultants that need to be assigned influence the assignment decision. Furthermore, each OTL member has different interests and believes and could decide differently on C2Pa decisions. These reasons lead to subjective and biased decision-making.
Time intense	The current C2Pa procedure is time intense since the OTL (team) performs the C2Pa procedure manually due to absence of a decision-support tool. The OTL (team) has 2 hours each for performing the C2Pa procedure, but the OTL (team) spends 4 hours on the C2Pa procedure.
Lack of long-term planning	The current C2Pa procedure focuses mostly on immediate needs, overlooking long-term requirements. This procedure therefore hinders strategic assignments and may result in a reactive approach instead of a proactive one.

Table 1.1: Negative consequences of BE NL' current C2Pa procedure

Due to negative consequences BE NL experiences by using their current C2Pa procedure, BE NL wants to make the C2Pa procedure structured and unambiguous to solve these negative consequences. This desire is therefore the starting point of this research. We formulate BE NL' research problem as follows:

"The absence of a structured and unambiguous C2Pa procedure hinders the OTL (team) with effectively managing the resource allocation, consultant satisfaction, project quality, and consultant assignment cost, resulting in suboptimal C2Pa that a) fail to balance the needs of all stakeholders involved, b) lack transparancy and visibility, c) are subjective & biased, d) are time intense, and e) lack long-term planning."

1.3 Problem statement

As concluded in Section 1.2, the current C2Pa procedure hinders the OTL (team) with effectively managing the resource allocation, consultant satisfaction, project quality, and consultant assignment cost resulting in suboptimal C2Pa. Therefore, this section elaborates upon this action problem by identifying the intermediate and core problems. Figure 1.4, gives an overview of the identified relations between the action problem, intermediate problems, and core problems.

The reason why BE NL' current C2Pa procedure is unstructured and unambiguous is threefold: 1) input data is incomplete or absent, 2) no clear measurable performance KPIs, and 3) complex decision-making in the C2Pa problem.

The reason for the incomplete or absent input data is threefold. First, the person who brought in the incoming and potential projects did not document the projects properly because this person did not know what information the OTL (team) needs. BE NL is aware of this problem and therefore already improved the information transfer by implementing staffing request templates (Figure C.1). Nevertheless, still large improvements can and must be made. Section 2.2 elaborates more on the procedure of how projects come to BE NL. Second, the information about the wishes and skills of the employees is not available or outdated. Third, BE NL currently does not have a data warehouse with relevant data for the C2Pa, meaning that the OTL (team) must acquire the data manually and from different sources. However, since the OTL (team) does this manually, only factors they consider relevant are taken into account leaving important information out. Section 2.5 elaborates more on this core problem. All three factors lead to incomplete or absent input data which hinders BE NL from creating a structured and unambiguous C2Pa procedure. We label these three core problems as non-influential since these problems are part of data and knowledge management and fall outside the scope of direct intervention.

No clear measurable performance KPIs complicate the evaluation of the objectives since this evaluation cannot be based on facts or numbers, but only on intuition and common sense which is vague and person dependent. No clear measurable performance KPIs therefore hinder the creation of a structured and unambiguous C2Pa procedure. An example of an ambiguous C2Pa is the situation where one of the OTL members chooses consultant 1 for project A, while another OTL member chooses consultant 2 for project A under the exact same circumstances. Subsection 2.4.1 elaborates more on the KPIs BE NL currently uses or wants to use.

The complex decision-making in the C2Pa procedure complicates the creation of a structured and unambiguous C2Pa procedure for BE NL, since complex decision-making leads to challenges related to objectivity, communication, and clarity. Complex decision-making creates challenges in maintaining clarity due to the multifaceted considerations involved like skills, cost, and satisfaction. Objectivity is compromised as subjectivity emerges in the interpretation of complex information like stakeholder needs. Communication becomes challenging as conveying intricate decision processes and outcomes to stakeholders becomes complex, leading to gaps in understanding and potential misunderstandings. Chapter 2 elaborates more on the complex decision-making of C2Pa procedure.

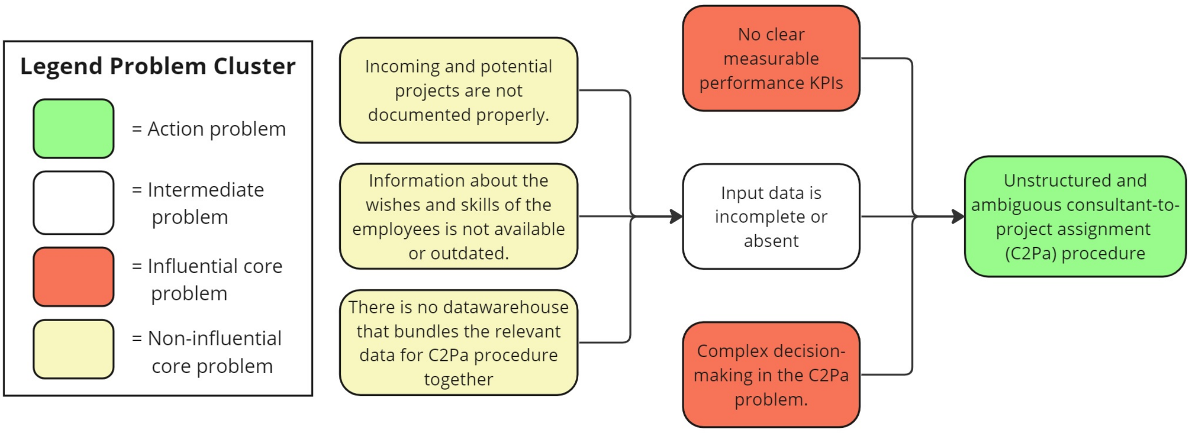

Figure 1.4: Overview of the problem cluster with regard to BE NL' C2Pa procedure

1.4 Research objective and research questions

This section describes the research goal in combination with the scope of the research, and the research questions. In this research we develop a C2Pa model that enhances BE NL's C2Pa procedure by transforming the current unstructured and ambiguous aspects into a well-defined and clear process. This modification aims to address the challenges posed by the existing procedure, ensuring that the C2Pa model is structured and unambiguous. The emphasis on structure and clarity is driven by the need to streamline the consultant-to-project assignment process, providing a more efficient and effective framework for project management within the organization. The research goal of this research is therefore:

"To develop a C2Pa model that helps improving BE NL' C2Pa procedure by making the C2Pa procedure structured and unambiguous."

After defining the research objective, we formulate several research questions and the main research question. We formulate the main research question as follows:

"How can BearingPoint Netherlands create a C2Pa model that helps improving the C2Pa procedure by making the C2Pa procedure structured and unambiguous?"

To answer the main research question, this chapter formulates and elaborates on the research questions.

1.4.1 Approach problem identification & analysis

The problem identification & analysis part consists of the first three chapters of this research. Chapter 1 introduces the problems involved with BE NL' current C2Pa procedure as well as the approach and the research questions to solve the problem. Chapter 2 deals with the analysis of the C2Pa procedure and the involved processes at BE NL. Chapter 3 discusses alternatives to the current C2Pa procedure provided by the literature review.

The research question we answer in Chapter 2 is:

1. What is the current situation of C2Pa procedure at BearingPoint Netherlands?

(a) What are the relevant consultant characteristics for the C2Pa procedure?
(b) What are the relevant project characteristics for the C2Pa procedure?
(c) What is the current C2Pa procedure at BearingPoint Netherlands?
(d) What are the KPIs, constraints, and requirements of the C2Pa procedure?
(e) What data is available at BE NL concerning the C2Pa procedure, and how is the (absent) data collected?

The research question we answer in Chapter 3 is:

2. What models and approaches related to the C2Pa are available in literature?

1.4.2 Approach solution generation & choice

Chapter 4 deals with the modelling approach for the C2Pa model. The research question we answer in Chapter 4 is:

3. What is a good modelling approach for the C2Pa problem?
   (a) What mathematical base model represents BE NL' C2Pa problem the best?
   (b) What necessary aspects is the chosen mathematical base model missing?

1.4.3 Approach solution experimentation

Chapter 5 deals with the results, analysis, and validation. The research question we answer in Chapter 5 is:

4. How does the model perform for different scenarios of the C2Pa problem?
   (a) Is the C2Pa obtained from the C2Pa model valid?
   (b) What are the different scenarios that we should consider to analyse the model?
   (c) What is the performance of the C2Pa model with respect to the different scenarios?

1.4.4 Approach evaluation & implementation

Chapter 6 deals with the evaluation and implementation. Chapter 6 covers the conclusion of the research, recommendations for implementing the C2Pa model for all service lines of BE NL, a discussion, and future research.

1.5 Research design

Section 1.4 presented the four research phases: problem identification & analysis, solution generation & choice, solution experimentation, and evaluation & implementation. These four research phases together form the research design. The research design systematically addresses the main research question by sequentially solving the (sub) research questions. This approach is a proved method for solving business problems (Heerkens and van Winden, 2017). Figure 1.5 visualizes the research design.

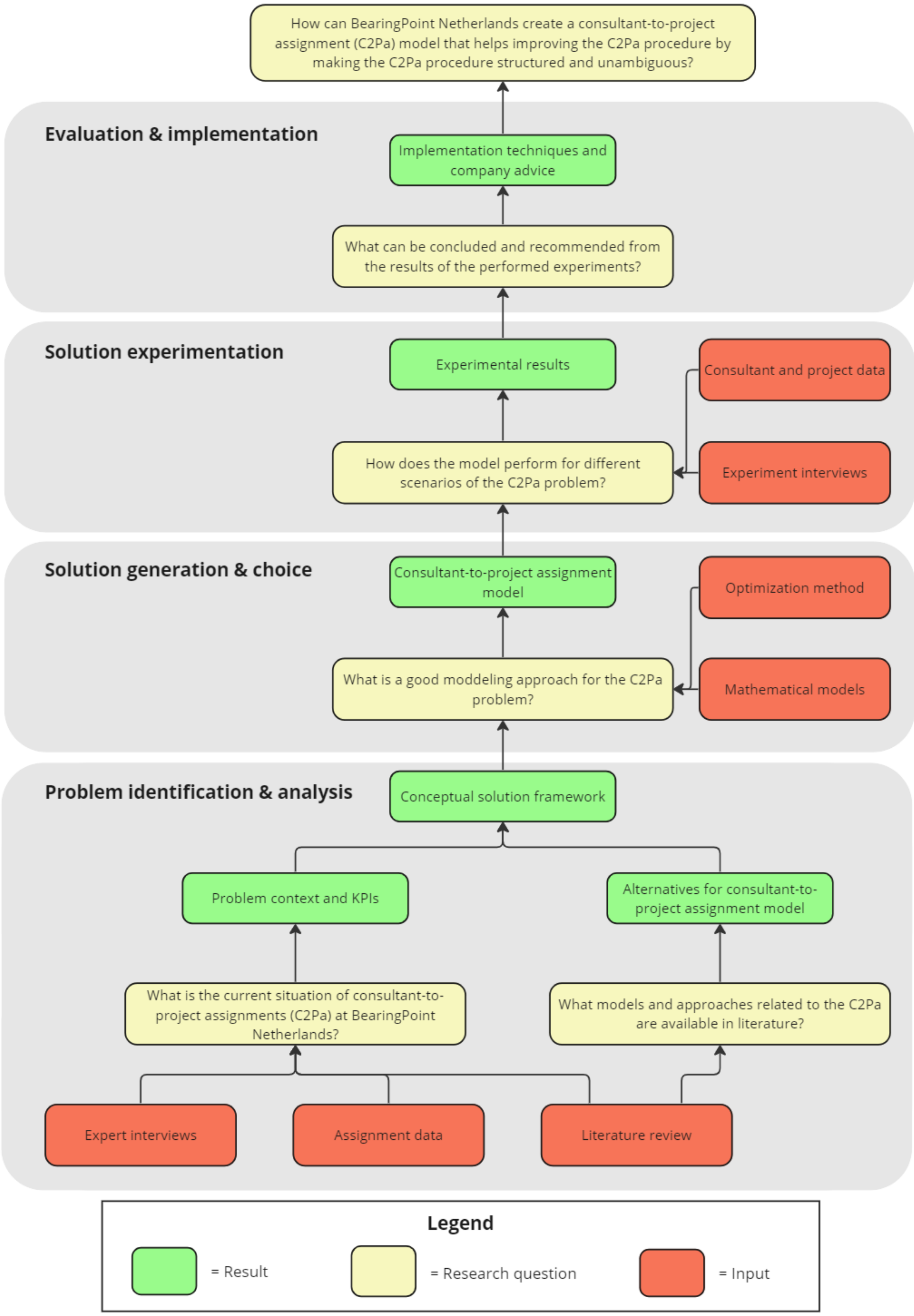

Figure 1.5: Visualization of the research design

2 CURRENT SITUATION

Chapter 1 described the introduction to the C2Pa problem BE NL encounters as well as the approach and the research questions to solve the problem. This chapter answers the research question: ”What is the current situation of C2Pa procedure at BE NL?”. To understand the C2Pa procedure we first describe two primary elements of the C2Pa: consultants and projects. Section 2.1 explains the relevant consultant related information, while Section 2.2 explains the relevant project related information. Section 2.3 describes the current C2Pa procedure at BE NL. Section 2.4 describes the KPIs, constraints, and requirements for BE NL’ C2Pa problem. Section 2.5 describes the data required for solving the consultant-to-assignment problem. At last, this chapter ends with a conclusion in Section 2.6.

2.1 Relevant consultant characteristics for the C2Pa procedure

BE NL has a diverse team consisting of consultants with different job positions, skillsets, and interests. Furthermore, all consultants are working in a specific service line and/or segment. Recognizing and leveraging the unique qualities of the consultants lead to a more fulfilling, inclusive, and productive work environment which is important for the consultants, and therefore for BE NL. Hence, this section elaborates upon these relevant consultant characteristics:

- Job positions: the job position a new hire at BE NL receives depends on the new hire’s experience and degree of education. BE NL has the following consultancy related job positions (in order of hierarchy): Management/ Business Analyst (MA), Consultant (C), Senior Consultant (SC), Manager (M), Senior Manager (SM), Director (D), and Partner (P). Figure 2.1 shows the distribution of consultants over the job positions in 2022. For the C2Pa process, BE indicated that only the MA, C, SC, and M need to be assigned. Table 2.1 shows the hourly cost per consultant depending on the job position. Next to the beforementioned job positions, BE NL also has sub functions that employees perform next to their job position. Relevant sub functions for this research are Engagement Manager (EM), and OTL (team). Section 1.2 already described the OTL (team), so this section describes the EM. The EM supports employees during projects and serves as a feedback channel to which consultants can reach out to in case of questions or issues. Next to this, the EM also talks with the companies to manage the relations between the company and BE NL and seeks for new business opportunities. Every project therefore has next to the consultant(s) one EM assigned. The EM has a job position of manager or higher.

Job posititon	**Cost per hour (€)**
Business/ management analyst	115
Consultant	127
Senior consultant	140
Manager	165

Table 2.1: Cost per hour per consultant level

Figure 2.1: Distribution of consultants over the job positions in 2022

- Service lines & segments: as Section 1.1 explained, BE NL operates in several markets on different expertises (D&A, TECH, C&G, and P&S). During the recruitment process, BE NL selects their candidates based on required experience and expertise with respect to the service line and sometimes the segment (market). Each consultant therefore always belongs to a specific service line within BE NL and this is important to consider for the C2Pa procedure. Figure 2.2 shows the distribution of consultants over the service lines in 2022.

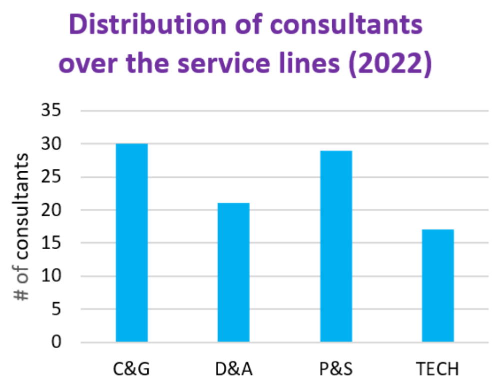

Figure 2.2: Distribution of consultants over the service lines in 2022

- Skillsets: eventhough a consultant works in a specific service line and/or segment, the consultant still encounters many diverse projects that require different skillsets. Incorporating the different skills and corresponding skill levels in the C2Pa procedure is therefore important. Appendix B shows an example of identified skills and the explanation of the possible skill levels for these skills for the D&A service line. The D&A service line already defined 23 skills and competences.
- Consultants' interest: the consultants' interest relates to the consultants' development ambitions and reflects where the consultant wants to work and develop on. Since many interests exists and most of these are not relevant for the C2Pa procedure the consultants filled in their interests based on the before identified skills with a skill satisfaction score according to Table B.2.
- Consultants' availability: the consultants' availability is an important aspect for the C2Pa procedure since this aspect determines the feasibility of the assignment. Currently the OTL (team) considers a consultant (partly) available if the consultant has an (partly) empty timetable. Updating the timetable in case of new project assignments or leave of absence

is therefore important. An entire project should fit within the consultant's availability in case the OTL assigns this consultant to the project since BE NL applies the business rule that the OTL (team) is not allowed to split a project over multiple consultants in case the project team consists of only one consultant.

2.2 Relevant project characteristics for the C2Pa procedure

In order to make good C2Pa, BE NL should also understand the project related aspects. This section describes the following relevant project aspects:

- Project team: the composition of a project team is an imporant project characteristic for the C2Pa procedure since the project team composition ensures that the elements of a project are addressed effectively, leading to higher chances of overall project success. Forming the project team involves identifying the right combination of consultants with complementary knowledge, job positions, expertise, and skills to complete the project. Approximately 33% of the projects requested in 2022 required a project team larger than 1 consultant. The EM is not part of the project team since the EM is not working on the required project skills. Each team member in a project team can have a different number of project hours. The project hours per team member remain constant during project duration.
- Skillsets: assessing the required skills and corresponding skill level for a project is essential for assigning the most suitable consultants to increase the chances of successful project delivery. The assessment of the required skillset for the project is done by using the identified skills and skill levels presented in Appendix B.
- Time windows: the project's earliest start and latest start time are crucial in determining the alignment and feasibility of the C2Pa with the available consultants. In 20-30% of the cases, BE NL has the freedom to choose their preferred start date for a project. Therefore, including the information if a project has a flexible start date is important for the C2Pa procedure.
- Project duration: the project duration of a project is a relevant project characteristic to consider for the C2Pa procedure since some projects may have tight deadlines (depending on the start time window in combination with the project duration) and/or the availability of the consultant with respect to the project duration, while others may allow for a more flexible schedule enabling more possible consultant(s) to be assigned to the project.
- Project priority: In the C2Pa problem, projects have different project priority due to characteristics of the projects. These characteristics are: signed (sold) projects, existing engagements, full-time assignments, long term projects, and/or internal projects. Subsection 2.4.3 elaborates more in detail about project priority and the project characteristics influencing the project priority.
- EM: Each project has an EM assigned. This assignment is known beforehand and predetermined.

2.3 Current C2Pa procedure at BearingPoint Netherlands

This section describes the different phases of the current C2Pa procedure at BE NL. Subsection 2.3.1 discusses the triggers of the current C2Pa procedure. Subsection 2.3.2 describes the process of assigning consultants to projects. Figure 2.3 visualizes the elements of the current C2Pa procedure. Subsection 2.3.3 ends this section by describing the scope and the scale of the current C2Pa procedure at BE NL.

2.3.1 Triggers of the current C2Pa procedure at BE NL

The C2Pa procedure starts when the OTL (team) gets an email with a filled in resource request (Figure C.1) for consultant(s) for a project. Before a resource request can be sent to the OTL (team) the project should satisfy three criteria: 1) the chance of getting the project is higher than 60%, 2) the proposal of the project is submitted, and 3) the project has a clear starting date. The first criterion is subjective and based on the assessment of the manager or higher job position that brought in the project opportunity. The C2Pa procedure starts by the following triggers:

- Project switches: A project switch is a switch of assigned consultant to the project. For a project switch the consultant personally reaches out to the responsible OTL who will then try to fulfill this request as soon as possible. Unfortunately, this mostly takes a long time because in the current C2Pa procedure there are 1) no insights in projects that will be available in the future which is necessary since the consultant needs another project and 2) the OTL (team) does not plan the C2Pa far ahead enough for other consultants to (easily) facilitate the project switch.
- Beach requests (internal project): When the OTL (team) receives a beach request, the OTL (team) first makes sure all resource requests for projects are handled since projects have priority. In case the OTL (team) dealt with all projects and there are still consultant(s) left with availability, the OTL (team) tries to search for the best match between the beach request and the required consultant(s).
- New projects and project extensions: For the resource requests for new projects and project extensions, the OTL (team) wants to receive at least one month before the consultant(s) are needed the request for the required consultant(s). However, currently this most of the time only happens two weeks in advance leading to stress for the OTL (team). The cause for this stress is because the OTL team quickly needs to provide the consultant(s) which is hard to do due to the current ad hoc C2Pa procedure.

2.3.2 The assignment process

The incoming resource requests always relate to one or more service lines, but the main responsible service line is not always clear from the start. In situations where the main responsible service line is clear, the responsible OTL selects the required consultant(s) based on common sense, consultants' availability, and business rules. However, in situations where the main responsible service line is unclear, the OTL team and BE NL' partners discuss the resource request during the weekly OTL meeting. In the weekly OTL meeting, next to the resource request for the projects with an unclear service line, the OTL members and the partners also discuss the difficult C2Pa and give an overview of the consultants they already matched individually. Difficult consultant assignments are assignments where the OTL is in doubt about, due to for example conflicting objectives, or because the OTL sees no good available match in the required period. The other OTL members or partners then give suggestions about consultants that might fit, discuss if BE NL should decline the project (also based on common sense, consultants' availability, and business rules), or discuss if BE NL should try to negotiate with the client about a different starting time and/or deadline for the project. For certain resource requests, the OTL (team) offers more consultants than required. The resource requester should then inform the OTL (team) with information about the choice for the chosen consultant(s).

After the weekly OTL meeting, the OTL team fills in or updates the C2Pa file and informs all involved stakeholders. The OTL approaches the stakeholders in the following order. First the consultant who is proposed will be asked if (s)he agrees. In case the consultant agrees the person who requested the consultant(s) will be informed. In case the consultant does not agree, the

OTL goes into conversation with this consultant until an agreement between the OTL and the consultant is reached. This could either be that the consultant accepts the assignment or that the OTL (team) starts the C2Pa procedure over again to find (an)other suitable consultant(s). The process from resource request until C2Pa takes at most one week since all assignments have to go through the weekly OTL meeting before the consultant is approached. So if the consultant(s) agree(s) the OTL contacts the resource requester with the name(s) of the required consultant(s). Most of the resource requests for a project want a consultant that can be assigned immediately. However, since the consultant can only start if the client has signed the contract, the consultant starts effectively two to four weeks after the resource request.

After the resource requester gets the information about the required consultant(s), the resource requester contacts the client which requested the project with the contract. For all resource requests except the project extension, the assigned consultants' availability gets blocked for the project after the client signs the contract. For project extensions with the same consultant(s) BE NL already blocks the consultant(s)' availability before the client signs the contract. With the current C2Pa procedure the situation that the same consultant is proposed for two different projects could occur. The client who signs the contract first then gets the specific consultant. The other client gets a consultant with a similiar skillset. If such a consultant is not available, BE NL has to disappoint the client and decline the project. However, in most cases BE NL is able to find a suitable consultant and the project is still executed. Since BE NL uses this way of matching consultants to projects, BE NL never promises a specific consultant for a project, but only a skillset the consultant should have.

Figure 2.3 visualizes all different steps mentioned in the current and previous subsections.

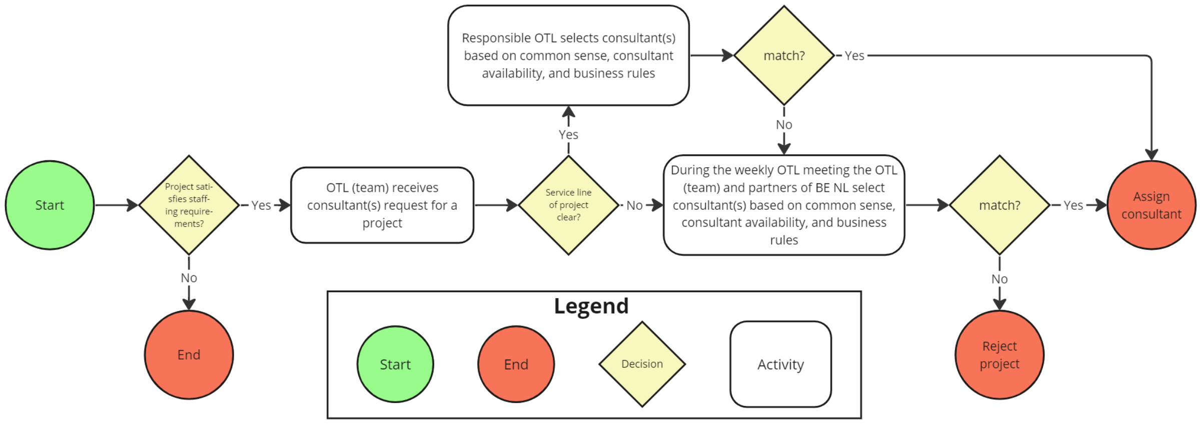

Figure 2.3: Visualization of the current C2Pa procedure at BE NL

2.3.3 The scope and scale of the current C2Pa procedure

The previously described C2Pa procedure happens ad hoc, meaning that each resource request triggers the C2Pa procedure and that the assignment decisions are made on a case-by-case basis. Therefore, the frequency of the C2Pa procedure depends on the resource requests the OTL (team) receives between the weekly OTL team meetings. On average, the OTL team matches consultants to 4 projects, and 5 beach request per week while there are at least 25 consultants that are available for matching every week. The consultants where the OTL team could not find a project for (internally or externally), determine their own planning with regards to trainings and helping other colleagues.

In the future, BE NL has the ambition to incorporate project opportunities (non-signed projects) and trainings in the consultant assignment procedure. This extension combined with the fact that BE NL has strong growth ambitions and aims for a growth from 80 consultant to 150 consultants in 2023, means that the current C2Pa procedure faces greater workload. Since the current C2Pa procedure is already having major limitations with the current workload (Section 1.2), this increase of workload will be problematic.

2.4 KPIs, constraints, and requirements of BE NL' C2Pa procedure

This section elaborates upon the KPIs, constraints, and the requirements of BE NL' C2Pa problem. Subsection 2.4.1 discusses the KPIs that BE NL finds important. Subsection 2.4.2 discusses the constraints. Subsection 2.4.3 discusses the requirements to meet the desired objectives.

2.4.1 KPIs for BE NL' C2Pa procedure

BE NL divides their strategy, vision, and goals over three categories: economical, enviromental, and societal. BE NL concretised these categories with respect to their three stakeholders which are their clients, their company (BE), and their consultants. The KPIs from BE NL' strategy, vision, and goals that are relevant for BE NL' C2Pa problem are:

- Consultant-to-project utilization
- Hourly cost of assigned consultants
- Consulant satisfaction
- C2Pa skill match

Consultant-to-project utilization rates KPI
The consultant-to-project utilization rates KPI is a KPI that keeps track of the utilization of the consultants. BE NL considers utilization as the percentage the consultant works on client project(s). For this KPI, BE NL wants to achieve the consultant-to-project utilization norms they specified per job position (Table 2.2). BE NL calculates the consultant-to-project utilization KPI per consultant individually by dividing the sum of the total chargeable hours plus the sum of EM hours of the consultant by the sum of the working hours of the consultant.

The chargeable hours are the total hours in a specified period a consultant worked on project(s) for client(s) that paid for this work. The EM hours are hours a consultant worked as EM on project(s). Per project the assigned EM gets a predefined number of EM hours per week until project completion. The working hours of a consultant refer to time period during which a consultant is expected to perform their job duties. Table 2.2 shows the current values of this KPI.

Job position	Target (norm) in %	Planned (reality) in %
Analyst	90	83
Consultant	80	79
Senior consultant	75	74
Manager	65	62

Table 2.2: Norm and reality of the consultant-to-project utilization rates KPI specified per job position for BE NL

Hourly cost of assigned consultants KPI
The hourly cost of assigned consultants KPI is a KPI that BE NL currently does not have but wants to use. The KPI should keep track of the weighted average hourly cost of the consultants that are assigned to projects. BE NL wants to minimize this cost by minimizing the overqualification. Consultants with a higher job positions are more expensive but also have more experience and a broader skillset. Consultants with a higher job position therefore fit to more projects than consultants with less experience and a smaller skillset. The reason BE NL wants to keep track of this KPI is because minimizing the weighted average hourly cost will stimulate the assigment of the lower job positions to the projects. This is beneficial in the following ways: 1) The consultants from lower job positions gain more experience and improve their skills leading to broader skillsets, and 2) the higher job positions fit more easy to projects, so assigning the lower job positions (which are harder to assign) gives more flexibility. The cost savings in terms of salary for a C2Pa planning with more lower job positions in comparison to one with more higher job positions is not mentioned since the client always pays for the consultant that is assigned. BE NL therefore does not benefit in terms of cost savings for this. Section 4.1.2 describes the calculation of this KPI as well as the norm and reality.

Consultant satisfaction KPI
The consultant satisfaction rates KPI is also a KPI that BE NL does not have but wants to use. In the current C2Pa procedure the consultant satisfaction is intuitively taken into account, however BE NL wants this KPI to be measurable and transparent. The KPI therefore should measure the average satisfaction of all assigned consultants to projects based on the project's characteristics and the consultant's wishes. Section 4.1.2 describes the calculation of this KPI as well as the norm and the reality.

C2Pa skill match KPI
The C2Pa skill match KPI is a KPI that assesses the quality of the work BE NL delivers at the client. Currently, the skill match is only intuitively taken into account and BE NL therefore wants to include this as a KPI. Section 4.1.2 describes the calculation of this KPI as well as the norm and the reality.

2.4.2 Constraints for BE NL' C2Pa procedure

To understand how we can improve the current C2Pa procedure at BE NL, we should understand the constraints that BE NL' C2Pa procedure has. We define a constraint as a limitation or restriction to the C2Pa procedure that must be taken into account. BE NL' stakeholder needs are mostly the cause for the constraints for BE NL' C2Pa procedure. This subsection describes the following constraints:

- Non-preemptive: BE NL uses the rule that consultants should finish the entire project once assigned to the project. The reason why BE NL decided to have a non-preemptive constraint is because project switching increases consultant inefficiency, creates additional work for the OTL (team), and is unpleasant for the client. However, under certain circumstances a project switch is allowed. Subsection 2.4.3 describes these circumstances.
- Consultants' availability: Since BE NL uses the non-preemptive constraint, the OTL can only assign projects to the consultant(s) in case the project fits entirely within the consultants' availability. The consultants' availability can never be exceeded. This also applies for EM hours. During the project duration, the EM on average spends 4 hours per week with EM responsibilities per project.
- Time windows: The time windows constraint (a project must start within its starting time window) is an important constraint when considering the possible consultants for the as-

signment to a project. Wider time windows for starting a project enlarges the chances for a larger consultants pool that could be assigned to the project leading to better performance of the C2Pa procedure.

- Team member constraints: BE NL uses multiple constraints regarding team members.
  - 1 consultant per team member role: A team member role can only be performed by one consultant and this consultant should remain assigned until the project is completed.
  - Not more consultants assigned to a project than team member slots: Unless the project is declined, exactly the number of consultants required for the project should be assigned to the project.
  - 1 team member per project skill: The skill the project requires should be covered by the project team members. A project skill can only be assigned to 1 of the team members.
  - Same skill assignment during project duration: During a project the team members remain assigned to the same skills. This cannot change over time.

2.4.3 Requirements for BE NL' C2Pa procedure

Next to understanding the constraints, understanding the requirements of BE NL' C2Pa problem is also important for improving the current C2Pa procedure at BE NL. We define a requirement as something the procedure must do or achieve to meet the desired objectives. BE NL' business rules inspire most of the requirements. This subsection describes the following requirements:

- Scheduling: Scheduling in the C2Pa problem involves determining when in the project's starting time window a project starts (in case the project is not declined).
- (Many-to-many) assignment: Assignment in the C2Pa problem involves matching consultants to projects. During the C2Pa procedure the OTL (team) has to deal with many-to-many assignments. In case of part-time projects (projects where consultants work fewer than 80% of their working hours on) the OTL tries to assign other projects to the consultant to reach the target utilization rates. Therefore the multiple projects to one consultant assignment is relevant to consider. The OTL also assigns at least two consultants to each project. This multiple consultants to one project situation is caused by following two constraints:
  - Project team: For larger projects, multiple consultants need to work on the same project which causes the OTL (team) to assign multiple consultants to a project.
  - EM: Even though a project is a small project, always one EM is responsible for monitoring the progress and keep close contact with the client as described in Section 2.1. In 2022, BE NL had 34 different EMs.
- Simultaneous scheduling and assignment: The timing of the projects (scheduling) determines the demand for the required consultants which influences the matching process (assignment). Both elements, are therefore dependent on each other and cannot be solved separately.
- Declining a project: BE NL uses the business rule to only decline a project in case accepting the project leads to an infeasible solution.
- Project switch: BE NL values the satisfaction of their consultants highly, meaning that BE NL listens to the needs and wishes of their consultants. Since consultants are most of

the time in the consultancy because they like project diversity, most of the consultants do not like being assigned to the same project for multiple years. Furthermore, projects can deviate from the consultant's expectation leading to dissatisfaction as well. This dissatisfaction can lead to a project switch request. As earlier described, project switches are inefficient. BE NL therefore, does not want that project switches to occur too often, but BE NL also does not want unsatisfied consultants. BE NL therefore thinks that 6 months is the perfect trade-off. The project switch rule is therefore: consultants who have been on a project for an extended period (longer than 6 months) can, in discussion with their EM and DM, indicate that they would like to switch. The OTL team will then try to facilitate this switch in joint discussion with the EM.

- 100% C2Pa for MA and C: BE NL believes that an employee learns the most when working on a project, so BE NL wants their management analysts and consultants to be working on projects as much as possible. Furthermore, to achieve the yearly averages as stated in Table 2.2 the OTL (team) has to try to plan the management analysts and consultants for 100% of the time on projects. Otherwise, the situation could occur that after a management analyst or a consultant finishes a project while the OTL (team) could not find a suitable project that starts immediately after the previous project leading to an utilization loss. Since the OTL (team) has no influence on this they should compensate for the risk that this occurs by trying to assigning the consultants and management analysts 100% of the time to projects.

- Project assignment order (project priority): In the C2Pa process, BE NL wants to consider the difference in project priority between the projects. BE NL has the following requirements (in order of importance):

  - Signed (sold) projects: Projects that already have a signed contract go before new (unsigned) projects, other non-chargeable work (beach or goodwill projects), and consultants' availability reservations for future projects.
  - Existing engagements over new: Existing engagements (BE NL' current clients) and extensions have priority above new engagements (projects from new clients).
  - Full-time assignment projects over part-time: Full-time C2Pa projects (projects with a consultant-to-project utilization higher than 80%) have priority over part-time C2Pa projects. BE NL uses this requirement since assigning consultants with multiple smaller projects to the utilization norm is harder then when achieving the utilization norm with assigning the consultant to one project. Furthermore, smaller (part-time) projects occur less complicating the assignment procedure even more.
  - Long-term projects over short-term: Long-term projects (projects that have processing times $\geq$ 6 months) have priority over short-term projects, since they give BE NL more financial stability.
  - Client projects over beach projects: Client projects have priority over beach (internal) projects, since beach projects do not generate revenue for BE NL and BE NL needs the revenue for their financial stability.

  According to the list, Table 2.3 shows the priority value weights in case certain priority aspects are included in the project. The OTL currently only takes the priority aspects intuitively into consideration. By conducting expert interviews we concretize the priority values. The values in Table 2.3 are the result of these interviews. The most important project for BE NL is a project of which the contract is signed (0.4), an existing engagement (0.3), with full time assignments (0.2), and a long project (0.1). This project has a total priority value of 1 (=0.4+0.3+0.2+0.1). This total priority value of 1 is also the maximum priority value a project could get since the project is either signed or unsigned or a beach project. Furthermore, the least important projects have a priority value of 0.01 in case the project is only a beach project. The reason why BE NL wants such a low value is because BE NL does not want that beach projects impact the C2Pa skill match KPI too much. The reason why the value cannot be equal to 0 is because the beach projects are not considered at all and the C2Pa skill match KPI becomes 0. This results that the C2Pa skill match KPI does not play a role in the C2Pa procedure anymore, which is undesired.

Priority aspects	**Priority value weights**
Signed contract	0.4
Existing engagement	0.3
Full time assignment	0.2
Long project	0.1
Unsigned contract (opportunity)	0.1
Beach (internal) project	0.01

Table 2.3: Project priority aspects value in case included in project

2.5 Data

This section describes and analyzes the relevant data for solving BE NL' C2Pa procedure. As mentioned in Section 1.3 the relevant input data is incomplete or absent due to absence of a data warehouse, inconsistency in documentation, and unavailability or outdated data. Figure 2.4 visualizes BE NL' current structure that the OTL (team) could collect manually versus the data warehouse that is necessary for solving BE NL' C2Pa procedure. The entities in the proposed database table marked in bold are either not present or need adaption to be useable.

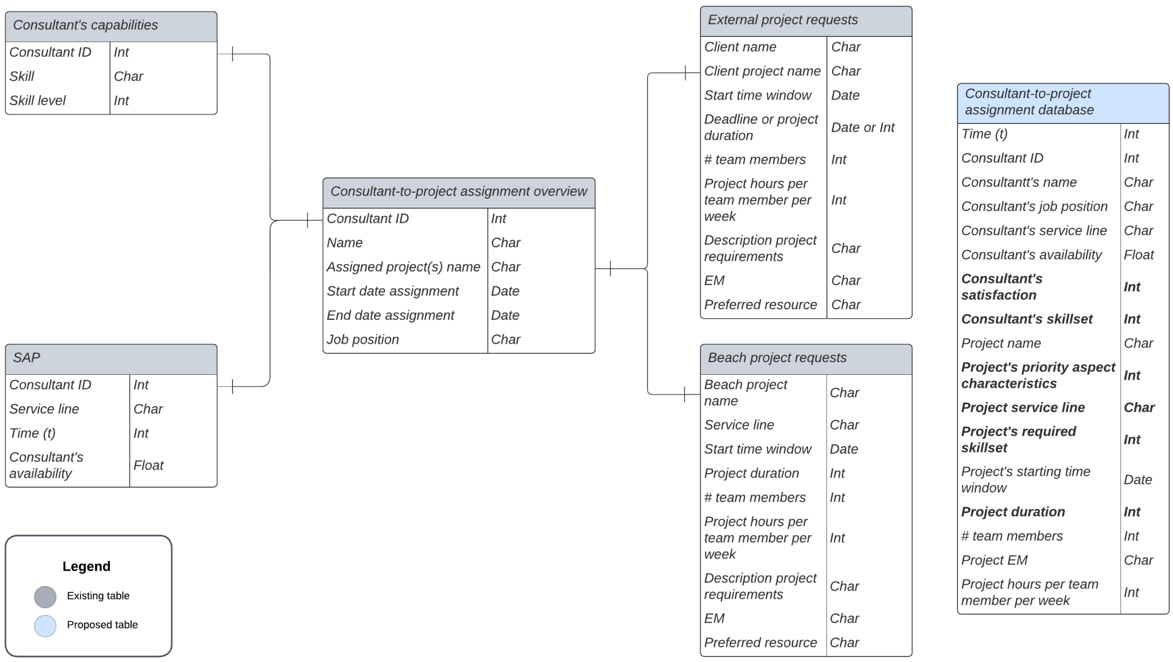

Figure 2.4: Visualization of the datasets relevant for the C2Pa procedure at BE NL

The relevant entities for BE NL' C2Pa procedure are defined as follows:

- Consultant ID: The consultant ID is a number that is associated with a specific consultant. This number serves as a unique identifier for each record, allowing efficient organization, retrieval, and manipulation of data.

- Consultant's name: The name describes the first and lastname of the consultant. The name is necessary since the OTL needs to contact the specific consultant in case the consultant is proposed to be assigned to a project.
- Consultant's job position: The job position is the description of the level of the consultant. The possible job positions are specified in Section 2.1.
- Consultant's service line: The service line is a description of the service line the consultant operates in. The possible service lines are specified in Section 2.1.
- Consultant's availability: The consultant's availability is an floating-point number that shows the number of hours a consultant still has available in time period t.
- Consultant's satisfaction: Currently BE NL does not have the consultant's satisfaction with respect to the capabilities or skills. We, therefore, collect the consultant's satisfaction with a survey that asks consultants their satisfaction level with respect to the skills according to Appendix B.
- Consultant's skillset: The input for the current consultants' skill levels is outdated (not representing their actual skills) or not available. Therefore, we conduct a survey that asks the consultants to rate their skills according to the identified capabilities and skills of Appendix B. This appendix also shows the skill level scale.
- Project name: The project name displays the name of the specific project making it possible to distinguish different project from each other.
- Project's priority aspect characteristics: The project's priority aspects characteristics are the binary values corresponding to the project priority aspects (Subsection 2.4.3). The project priority aspects are: signed contract, existing engagement, full time assignment, long project, beach project, or unsigned contract (opportunity).
- Project service line: The project service line describes the service line(s) expertise the project requires for completion. Currently BE NL only register this for beach projects. We therefore conduct an expert interview to identify the service lines of the client projects in the past. The possible service lines are specified in Section 2.1.
- Project's required skillset: Currently BE NL does not classify the project's required skillset according to the capabilities and skills. We collect this information via expert interview with the OTL team to identify the project's required skillset of projects in the past according to Appendix B.
- Project's starting time window: The project's starting time window consists of the earliest start time of a project and the latest start time of a project to ensure the project is finished before the deadline. In case no starting time flexibility is possible, the earliest start time equals the latest start time. The earliest start time and latest start time are provided in date format.
- Project duration: The project duration is an integer that represents the amount of weeks that are necessary for completing the project. The project duration is always known.
- # team members: The # (number of) team members specifies the integer amount of consultants necessary for executing the project.
- Project EM: The project EM specifies the name of the EM for the project.

- Project hours per team member per week: The project hours per team member per week is an integer specifying the allocation hours to each team member per week during the project duration. In case multiple consultants are assigned to one project, the number of project skills assigned to each team member are based on the proportion of project hours the team member works on the project.

2.6 Conclusion

This chapter extended the introduction of BE NL' problem provided in Chapter 1 by providing the current situation of the C2Pa procedure at BE NL to create the necessary context. Relevant consultant characteristics are the job positions, service lines & segments, skillsets, consultants' interest, and the consultants' availability. Relevant project characteristics are the project team, skillsets, time windows, project duration, project priority, and the engagement manager. Chapter 3 investigates the existing literature on these characteristics. After the context description, this chapter continued with a detailed description of the current C2Pa procedure at BE NL. We described this procedure by explaining the triggers of the procedure, the assignment process, and a scope and scale of the procedure. After the current C2Pa procedure, this chapter described the KPIs, constraints, and requirements of the C2Pa problem BE NL encounters. Chapter 3 also investigates the existing literature on the KPIs, constraints, and requirements. At last, this section presents the required data for solving the C2Pa problem.

3 LITERATURE REVIEW

This chapter answers the research question "What models and approaches related to the C2Pa problem are available in literature?". The structure of this chapter is as follows: Section 3.1 describes the application area of this research, the C2Pa problem. Section 3.2 reviews literature related to the C2Pa application area to come up with the most suitable problem base for the C2Pa problem. Section 3.3 explores how existing literature addresses the missing elements between the C2Pa problem and the most suitable problem type. Section 3.4 describes the solution methodologies for solving the C2Pa problem. Section 3.5 wraps up the literature review.

3.1 C2Pa application area

This section starts by giving a general description of the C2Pa application area. This section then continues by extending the general description by providing the needs as well as the relevance, significance, and the broader context of the of the C2Pa application area.

3.1.1 General description

The C2Pa is an application area that deals with developing techniques and methods to match consultants to projects in a way that maximizes the project's success probability while also ensuring client and consultant satisfaction (Hossein et al., 2015). This application area gained significant interest in recent years due to (Poulfelt et al. (2017), Ernst et al. (2004)):

- the growing importance of having the right consultants with the right skills and expertise to perform the projects successfully
- more service oriented and cost conscious businesses in a global environment
- the increasing complexity of projects

One aspect of the C2Pa application area involves developing models and algorithms that identify the best assignment match based on various criteria, such as preferences, consultant's skills, availability, and experience, as well as the budget, timeline, location, and project's requirements. These models and algorithms may use optimization techniques for making the best match (Martinovic and Savic, 2019). Another aspect of this application area focuses on investigating factors that affect the consultant's willingness to work on a particular project (consultant's wishes), such as the project's scope, risks, complexity, theme, company, as well as the potential growth and learning opportunities. Understanding these consultant factors can help consulting firms and project managers to design and/or attain more attractive projects to retain and attract top talents. Overall, C2Pa is an important application area with practical implications for consulting companies and their customers. By developing and implementing effective assignment strategies and tools, companies can enhance their reputation, increase their profitability, improve their project success rates, while providing clients with better quality, and their consultants with rewarding and more satisfying work experiences.

3.1.2 Relevance, significance, and broader context

Historically, the consulting industry undergone major changes over the past few decades. Examples of these changes are the increasing complexity of business operations and the rise of globalization. These changes led to a growing demand for specialized consulting services. The consultancy market has a highly competitive nature, where continuously adaption of consultancy companies to meet the changing needs of their clients is a must to survive. The demand for specialized consulting services in combination with this quick changing environment emphasizes the need for efficient C2Pa procedures (Poulfelt et al., 2017) (Wang et al., 2023).

The social context of the C2Pa is mainly about the characteristics of (professional) consultants. Mobile and highly skilled workforce characterizes the consultancy sector. Consultants often have the desire to perform challenging projects, are highly motivated, want to advance their careers, and have advanced degrees in fields such as engineering, business, and technology. Furthermore, professional consultants evolve and not just stick to their assigned role. Professional consultant take responsibility, do whatever it takes to finish the project, are team players, are loyal, are observant, are honest, listen to their clients' needs, commit to quality, and show initiative (Poulfelt et al., 2010).

The economical context of the C2Pa is about the size of the consultancy sector where the C2Pa happens. The consultancy industry is a significant contributor to the global economy, valued at almost 900 billion U.S. dollars in 2021 (The Business Research Company, 2021) (Statista, 2022b). The consultancy sector employs millions of people worldwide and provides its consulting services across a broad range of sectors amongst others government, finance, healthcare, and technology (Statista, 2022a). The demand for consulting services is closely linked with broader economic trends such as geopolitical developments, changes in business cycles, and shifts in industry dynamics.

As described in Section 1.3, the current C2Pa procedure of BE NL is unstructured and ambiguous leading to the problems mentioned in Section 1.2. Not only BE NL experiences these problems, also in literature, there is need for a structured and systematic approaches to decision-making in complex C2Pa scenarios due to the need for dealing with complexity, creating consistency, reducing risk, creating transparency, and improved optimization (Gregory et al., 2012). Unfortunately, this application area does not have a standard problem base for solving the problem.

3.2 Problem base

In the C2Pa application area all activities are executed in the form of projects. Efficient project management (PM) is therefore crucial. PM applies skills, knowledge, technologies, and tools to project activities. PM organizes, plans, controls, and coordinates these project activities to achieve the set objectives. A large part of PM is project scheduling. Project scheduling aims to determine the time schedule for implementing project activities and to allocate resources for activities under certain constraints. Project activities compete for limited resources and follow predetermined precedence relationships, leading to the optimum schedule for attaining specific goals (Ding et al., 2023).

Dike (1964) defines this situation as the Resource-Constrained Project Scheduling Problem (RCPSP), which became the standard problem for project scheduling. The RCPSP is an NP-hard problem (Hartmann and Briskorn, 2022). A summary of the standard RCPSP is as follows: A project has J activities and each activity has processing time d_j. Once an activity is started, the activity cannot be interrupted until completion (non-preemptive property). Between (some) activities precendence relationships exist due to (technological) requirements. The (technological) requirements are in the set of predecessors (P_j). P_j indicates that activity j cannot be started before each of the predecessors w ($w \in P_j$) is completed. To complete an activity, K types of renewable resources are required. Renewable resources refer to resources that are not consumed with the completion of activities, such as human resources. In each period, activity j requires r_{jk} units of resource k when processing is carried out. The availability of resource k is assumed to be constant during all periods and represented by R_k and cannot be exceeded. RCPSP also considers two dummy activities: $j = 0$ and $j = J + 1$, for which the resource requests and durations are zero. These dummy activities represent the start and completion of the project. The objective of the RCPSP is to find a schedule that leads to the earliest completion time of the project. At last, all information required for the RCPSP is assumed to be deterministic and known in advance.

Although, the standard RCPSP knowledge base is extensive and powerful, it cannot address the problem encountered in the C2Pa application area. The single-skill case does not take into account that human resources have multiple skills which is relevant to consider in the C2Pa problem. The multi-skill extension of the RCPSP (MS-RCPSP) is capable of depicting this multi-skill case and simultaneously schedules activities and assigns resources to meet demand (Ding et al., 2023). Simultaneously solving the two resource allocation steps (scheduling and assigning) is imporant for the C2Pa problem since in a project context these two steps are interrelated. Furthermore, in the C2Pa problem we have multiple projects simultaneously that need to share (limited) resources, require diverse skill sets, and could have conflicting priorities. The single-project case of the standard RCPSP cannot represent these multi-project aspects. The multi-project extension of the RCPSP (RCMPSP) is capable of depicting this multi-project case (Ding et al., 2023).

A combined MS-RCPSP and RCMPSP model solves both the multi-project and multi-skill requirement, however, such a model still considers tasks, precendence of tasks, and the scheduling of tasks. Heimerl and Kolisch (2010a) therefore develop a simultaneous multi-project scheduling and multi-skilled staff assignment model which is a special case of a combined MS-RCPSP and RCMPSP model. Different to other combined MS-RCPSP and RCMPSP models, Heimerl and Kolisch's model:

- does not consider tasks, precedence of tasks, and the scheduling of tasks
- does not consider project selection
- does not consider learning and forgetting (not account for the potential changes in efficiency over time due to learning effects or the loss of efficiency due to forgetting) but heterogeneous and static efficiencies (effiency over time remains constant)
- is represented as a MILP which can be solved to optimality due to tight LP-relaxations (even for large instances)
- considers internal (employees) and external (subcontractors) resources
- has the fundamental assumption that each employee can work in each period at multiple projects, possibly using different skills

Heimerl and Kolisch's model considers multiple projects simultaneously that require specific skills that should be done to complete the project. The model assigns employees to the skills based on their capacity (availability) and skill set. The order of the required skills for a project is fixed (no scheduling needed), but the project itself as a whole can be scheduled. Project p

has fixed duration d_p and in project period $q = 1, ..., d_p$ project p requests r_{psq} work units of skill s. A project must start within its time window [ES_p, LS_p] where ES_p is the earliest start period of project p and LS_p the latest. The latest finish period is calculated as $LF_p = LS_p + d_p - 1$ where the time line goes from period $t = 1$ to $t = T$ and T denotes the planning horizon. The model has a single-objective that minimises the labor costs of external and internal resources. The internal labor costs are similar to the external labor costs except that the efficiency of the employees on the skills influences the total working time (high efficiency, less time needed), and that there is distinction between overtime and regular working time cost. The cost KPI is similar to the one required in the C2Pa application area, except that we do not need to consider external resources, overtime, and efficiency that impacts the working hours.

Despite that the model of Heimerl and Kolisch (2010a) has a good fit for the C2Pa application area, the C2Pa problem needs to be multi-objective, misses project priorities, skill levels, and a project team constraint that makes sure a predetermined number of resources is assigned to a project. Table 3.1 summarizes relevant literature extending the model of Heimerl and Kolisch (2010a). None of the extended models turns out to be a better problem base than the original model. The reason for this is because the extended models add too much unnecessary complexity to the model without adding enough value for becoming the problem base for C2Pa problem. However, the extended models provide useful aspects for extending the model of Heimerl and Kolisch (2010a).

Chen et al. (2014) extend the model of Heimerl and Kolisch (2010a) by adding a parameter that specifies the assigned number of employees for task k of project j (N_{jk}). Although the C2Pa problem does have projects that consists of tasks, the problem has to respect the predetermined project team sizes. This parameter could therefore be adapted to represent the project team size constraint for the C2Pa problem.

Chen et al. (2020) maximize the quality of a project in their MS-RCPSP model by assessesing the quality as the weighted sum of the development qualities of the projects in the portfolio. The development quality of a project is calculated as the average efficiency of the employee assigned to the project based on the required skills. Chen et al. (2020) quality KPI is similar to the C2Pa skill match KPI.

Reference	**Extension(s)**	**Useful aspect(s) for C2Pa problem**
(Heimerl and Kolisch, 2010b)	Learning and forgetting effect, Single-project	No
(Kolisch and Heimerl, 2012)	Task scheduling	No
(Chen et al., 2014)	Task scheduling, Specified number of employees for task k of project j, Multi-objective	Yes
(Walter and Zimmermann, 2014)	Hierarchical approach of project selection, workforce assignment, and utilization leveling	No
(Chen et al., 2017)	Learning and forgetting effect, Multi-objective, 1 skill per employee per project, Variable task duration, Task scheduling	No
(Felberbauer et al., 2019)	General model, Stochastic task duration, Task scheduling	No
(Chen et al., 2020)	Multi-objective (Skill match KPI), Learning effect, Task scheduling	Yes

Table 3.1: Extensions to the model of Heimerl and Kolisch (2010a)

3.3 Solution for gaps

Subsection 3.2 identified gaps between the C2Pa problem and the model of Heimerl and Kolisch (2010a) and related relevent model extensions. Since very few literature considers simultaneous multi-project scheduling and multi-skill staffing (Chen et al., 2017), we could not solve these gaps with simultaneous multi-project scheduling and multi-skill staffing models. We therefore broadened our literature search for solving these gaps to related RCPSP MILP models. We discuss the following gaps: project priority, consultant-to-project utilization rates, and consultant satisfaction rates.

3.3.1 Project priority

One of the extensions of RCMPSP models, is the project priority characteristic. The (project) weight extension of the RCMPSP enables project preferences or priorities to be taken into account during the assignment and scheduling process. The (project) weight extension is added to the RCMPSP since in several environments, (project) priorities or preferences are needed for modelling daily operations (e.g. a hospital emergency room) (Gómez Sánchez et al., 2022). A common approach for modelling weights is by adding a parameter that assesses the weight (priority degree) of a project and including this weight parameter in the objective value. For example, Afruzi et al. (2020) uses this method.

3.3.2 Consultant-to-project utilization rates

Zabihi et al. (2019) present a MS-RCPSP model that minimizes the total salary of the workforce, minimizes the total completion time of the activities, and maximizes the efficiency of the workforce on performing skills related to activities. The last objective has potential for solving the identified gap for the consultant-to-project utilization rates KPI. Zabihi et al. (2019) model the efficiency objective as "the average efficiency of workforces (employees) allocated to the project's different skills" [p.198]. Equation 3.1 shows this objective where M is the number of workforce (employees), K is the number of skills, EF_{mk} is the efficiency of workforce m on skill k, and r_{mk} is the binary decision variable that equals 1 if workforce m can do skill k and 0 otherwise. Zabihi et al. (2019) compute the average availability by dividing the sum of all efficiencies for all skills and workforce over the sum of the assigned workforces to the skills for all skills and workforce.

$$Max\ Z = \frac{\sum_{m=1}^{M} \sum_{k=1}^{K} EF_{mk}}{\sum_{m=1}^{M} \sum_{k=1}^{K} r_{mk}} \tag{3.1}$$

3.3.3 Consultant satisfaction rates

The consultant satisfaction rates KPI is a KPI not seen in RCPSP models. Abboud et al. (1998) present an approach for calculating the consultant satisfaction rates KPI. They focus on a real size manpower allocation problem that needs to distribute salesmen force over the company's branches. Equation 3.2 shows the calculation of the salesmen satisfaction KPI where s_{ij} is the satisfaction of the i^{th} salesman when assigned to the j^{th} branch and x_{ij} is the binary decision that equals 1 in case salesman i is assigned to branch j and 0 otherwise. Furthermore, n is the total number of salesmen and m is total number of branches.

$$Max\ Z = \sum_{j=1}^{m} s_{ij} x_{ij},\ i = 1, ..., n \tag{3.2}$$

3.4 Solution methodologies

This section elaborates on solution methodologies by discussing the mathematical formulation type in Subsection 3.4.1, computation time in Subsection 3.4.2, metaheuristics in Subsection 3.4.3, and how to deal with multiple objectives in Subsection 3.4.4

3.4.1 Mathematical formulation type

The simultaneous scheduling and assignment is often solved modelled as a Mixed-Integer Linear Programming (MILP) (Haghi et al., 2017) (Heimerl and Kolisch, 2010a) (Kolisch and Heimerl, 2012). However, very few literature considers simultaneous multi-project scheduling and multi-skill staffing. Therefore, we also consider the choices for mathematical formulations of the MS-RCPSP and RCMPSP models. The most used mathematical formulation type for MS-RCPSP is the MILP model which is used in 54.2% of the cases (Afshar-Nadjafi, 2021). The most used mathematical formulation for solving the RCMPSP exact are linear-programming based techniques which are used 73% of the time (Gómez Sánchez et al., 2022). MILP is also part of this group.

The reasons why literature uses MILP so often for these types of problems is the fact that MILP handles the resource-constraints needed for these problems naturally, MILP is flexible in terms of constraints, objectives and variables, MILP can handle the multi-skill consideration, and the ability of MILP to handle complexity that is often involved with these models.

Next to the fact that literature uses MILP quite often for similar problems and the advantages of using MILP, there are also some disadvantages of using MILP. The first disadvantage is that in a MILP all equations should contain linear variable relationships. The second disadvantage is that the computational time should be considered since the MILP's computational time can increase rapidly as the size of the problem grows. Large-scale scheduling problems with numereous projects, tasks, and resources can therefore be computational heavy leading to long solution times. Determining if the MILP could be solved exact in a reasonable time or needs a (meta)heuristic is therefore important.

3.4.2 Computational time

To get a feeling for the computational time of the C2Pa problem, we look at problem instances and computational time of similar simultaneous scheduling and staffing models. Heimerl and Kolisch (2010a) prove that simultaneous scheduling and staffing models are NP-hard, meaning that solving large and medium-scaled problem instances of this problem type go beyond the scope of exact algorithms (Kolisch and Heimerl, 2012). Heimerl and Kolisch (2010a) solve a small instance of the problem to optimality and show that increasing time windows results in sharp increases in computational time due to the increasing number of binary variables. Furthermore, they show that the number of projects and skills per resource has a linear influence on the computational time due to the growing number of continuous variables. Haghi et al. (2017) show two effective metaheuristics for solving medium to large-scale instances of the simultaneous scheduling and staffing problem. Although, both methods worked well in the small instance problem, simulated annealing outperformed genetic algorithm on the large-scale instances on both CPU-time and accuracy measures.

3.4.3 Metaheuristics

As discussed in Subsection 3.4.2, simultaneous scheduling and staffing is a NP-hard problem. Due to the NP-hardness of these problem types (meta)heuristics and hybrid approaches are developed to find near-optimal solutions in polynomial time. The most popular solution methodology for simultaneous scheduling and staffing problem are metaheuristics such as Genetic Algorithm (GA), Simulated Annealing (SA), and Tabu Search (TS) (Haghi et al., 2017) (Kolisch and Heimerl, 2012). Of all mentioned metaheuristics, SA is usually easily implemented. Furthermore, Haghi et al. (2017) prove that SA for simultaneous scheduling and staffing problems outperforms the other metaheuristics in both computational time and performance.

SA is a probabilistic search technique that approaches the global optimum. By accepting poorer solutions with some probability, SA can escape local optima. An initial solution is needed for the general SA approach. The initialization solution phase of a SA algorithm involves generating an initial solution for the problem at hand. While a feasible initial solution (solution that satisfies the problem's constraints) is desirable, having a feasible initial solution is not always a strict requirement. Whether this is a strict requirement depends on the problem and the specific implementation of the algorithm. In some cases, having a feasible initial solution can help the SA algorithm to start in a region of the solution space that is closer to optimal. This can potentially improve the overall performance and speed up convergence of the SA process. However, if finding a feasible initial solution is time-consuming or difficult, some implementations of SA might tolerate an infeasible initial solution. The SA algorithm will then work to gradually explore the solution space, including feasible and infeasible regions, as it iteratively progresses.

Furthermore, SA requires the following parameters: a starting temperature, cooling factor, and Markov chain length. In SA, temperature serves as a control parameter that regulates the probability of accepting worse solutions during the optimization process. The temperature starts high allowing for exploration of the solution space and then gradually decreases. Lower temperatures prioritize exploitation, helping converge toward optimal solutions. A rule of thumb for determining the initial temperature (T_{start}): Choose T_{start} such that almost every transition is possible to ensure high diversification at the start of the algorithm (Kirkpatrick et al., 1983). This means that T_{start} is chosen such that the initial *acceptance ratio* is approximately 1.

$$acceptance\ ratio = \frac{\#\ of\ accepted\ worse\ transitions}{\#\ of\ proposed\ worse\ transitions} \tag{3.3}$$

The temperature changes after M iterations, where M represents the Markov chain length. The Markov chain length can be static (fixed M) or dynamic (after each chain increase M, because the probability of a transition decreases). A rule of thumb for determining the Markov chain length is setting the length to the number of neighbor-solutions. Neighbor solutions are generated by making small changes to the current solution. The last parameter is the cooling factor. The cooling factor is part of a cooling scheme. Several cooling schemes for updating the temperature exist. A commonly used cooling scheme for SA is $T_{k+1} = \alpha T_k$ (Rader, 2010). α denotes the cooling factor and follows from the Markov chain length and the available computation time (# iterations).

The SA algorithm generates neighbor solutions by modifying the existing one. In the SA algorithm, the neighborhood functions phase plays an important role in the exploration of the solution space. This phase consists of defining and using various neighborhood moves to the current solution in order to explore nearby potential solutions. These moves alter the current solution while ensuring feasibility. Neighborhood functions can include a range of modifications, from subtle adjustments to more significant changes. The decision on the type of move can vary and might encompass swaps, insertions, deletions, or other transformations that alter the solution. The goal of the neighborhood function is to introduce diversity in the search process, allowing the SA algorithm to explore different regions of the solution space. For good performance of the SA algorithm, suitable neighborhood operators should be chosen that reach every solution (connectivity) in as few transitions as possible.

If the neighboring solution is superior to the existing one, it is accepted. The solution can nevertheless be accepted against a probability if it is not better. The Boltzmann distribution is used to determine the likelihood of accepting poorer solutions (Equation 3.4). The chance of acceptance follows a cooling strategy and is iteratively decreasing. When the temperature is high, there is a greater likelihood that less desirable options are accepted. The likelihood of adopting poorer solutions reduces as the temperature gradually drops with the cooling factor. Diversification is the acceptance of many inferior solutions, and intensification is the gradual reduction of the likelihood of accepting worse alternatives (Kirkpatrick et al., 1983) (Amine, 2019) (Delahaye et al., 2019) (Henderson et al., 2003).

$$RandomNumber \leq \epsilon^{\frac{CurrentSolution - NeighborSolution}{T}} \tag{3.4}$$

The original (before described) SA algorithm can only deal with single objective combinatorial problems (Suman and Kumar, 2006).

3.4.4 Multi-objective optimization

As anticipated, our C2Pa problem deals with multiple objectives, making the problem a multi-objective problem (MOP). When dealing with a MOP, it is very uncommon that there exists a solution that is optimal for all objectives, as the objectives might be conflicting. We can deal with this in two ways: reduce the MOP to a single-objective problem with a single objective value, or consider all objectives at the same time, leading to multiple possible solutions (Pareto front).

For the latter case, there are two methods: Pareto optimization or indicator-based methods. Pareto optimization focuses on solutions that are non-dominated. Non-dominated means that no solution is better than another solution in all objectives. Pareto optimization aims to create a diverse set of solutions that represent various trade-offs between conflicting objectives. In contrast with pareto optimization, indicator-based methods assess the quality of the solutions by calculating performance indicators instead of using the concept of dominance (Talbi, 2009).

Reducing the MOP to a single-objective problem can be done by criterion-based methods or scalarization to aggregate the objectives. Often used scalarization methods are MCGP and the weighted sum method (Talbi, 2009). The weighted sum method lacks flexibility since only fixed weights could be specified and has loss of information (all objectives are aggregated into one single objective value). The MCGP has the following disadvantages (Chang, 2008):

- Complexity. The multiplicative terms of binary variables in the standard MCGP model lead to difficult implementation and is not easy to understand by consultant-to-project planners. Complexity of a MCGP model is therefore a disadvantage compared to the weighted sum method.
- Weight tuning. The standard MCGP model has more weights (w_k and α_k) than the weighted sum method. These extra weights need to be determined which can be difficult.

- Solution space exploration. Another disadvantage of using multiple aspiration levels, is that this possibly leads to a larger solution space to explore. Finding an optimal/ good solution can therefore be more computationally intense and time-consuming.

Chang (2008) solves two of the three limitations of the MCGP models with his revised MCGP model. Chang (2008) replaces the multiplicative terms of binary variables, with an alternative method that is easily understood by industrial participants and has a linear form that can easily be solved by common linear programming packages (solving the complexity limitation of the standard MCGP). Furthermore, the revised MCGP model is also proven to be superior to the standard MCGP in terms of running times solving the solution space exploration limitation as well. The only difficulty that remains for the revised MCGP model is the determination of the weights. This difficulty has to be taken into account during implementation. Several methods exist in literature for determining the weights: equal weights, analytical hierarchy process (AHP), best-worst method (BWM), sensitivity analysis, and consultation with experts (Şahin, 2020).

Wang et al. (2022) use $g_{k,max}$ for the maximum aspiration level of goal k in case "the more the better applies" and $g_{k,min}$ otherwise. This extension is added to avoid underestimation of decision making (Chang, 2008). Chang formulated this MCGP model as follows:

$$Min \sum_{k=1}^{n}[w_k(d_k^+ + d_k^-) + \alpha_k(e_k^+ + e_k^-)] \tag{3.5}$$

$$subject\ to$$

$$f_k(x) - d_k^+ + d_k^- = y_k \quad k = 1, 2, ..., n \tag{3.6}$$

$$y_k - e_k^+ + e_k^- = g_{k,max}\ or\ g_{k,min} \quad k = 1, 2, ..., n \tag{3.7}$$

$$g_{k,min} \leq y_k \leq g_{k,max} \quad k = 1, 2, ..., n \tag{3.8}$$

$$d_k^+, d_k^-, e_k^+, e_k^- \geq 0 \quad k = 1, 2, ..., n \tag{3.9}$$

y_k is a continuous variable that represents a value in the aspiration level interval range of the k^{th} goal. The range is between $g_{k,min}$ and $g_{k,max}$. $f_k(x)$ is the linear function of $x_1, x_2, ..., x_n$ for the k^{th} goal. d_k^+ and d_k^- are the positive and negative deviation to the absolute difference between $f_k(x)$ and y_k (difference between the KPI and continuous variable that represents a value in the aspiration level interval range), while e_k^+ and e_k^- are the positive and negative deviations attached to $|y_k - (g_{k,max}\ or\ g_{k,min})|$ (Difference continuous variable that represents a value in the aspiration level interval range and the desired minimum or maximum aspiration level). α_k is the weight attached to the sum of deviations of $|y_k - (g_{k,max}\ or\ g_{k,min})|$ and w_k is the weight attached to the k^{th} goal (Chang, 2008).

3.5 Conclusion

This chapter started with describing the C2Pa application area and its needs. The C2Pa application area deals with methods to match consultants to projects in a way that maximizes the project's success probability while also ensuring client and consultant satisfaction. The C2Pa application area does not have a standard problem base for solving the C2Pa problem. During the literature search we found that the simultaneous multi-project scheduling and multi-skill staffing problem of Heimerl and Kolisch (2010a) was the most suitable for modelling the C2Pa problem. However this model and related simulaneous multi-project scheduling and multi-skill staffing models were not able to solve the entire C2Pa problem. We therefore conducted future research with respect to the missing elements: project priority (Afruzi et al., 2020), consultant-to-project utilization rates (Zabihi et al., 2019), and consultant satisfaction rates (Abboud et al., 1998). Chapter 4 uses these findings as base for the modelling approach.

Next to modelling the C2Pa problem, we also conducted research for solution methodologies so we could solve the problem. This research included research to most suitable mathematical formulation types, computational complexity, most suitable metaheuristics, and how to deal with multi-objective problems. The most suitable mathematical formulation type turned out to be MILP. However, for large instances MILP can be computational intensive and a metaheuristic is therefore often used for simultaneous scheduling and staffing problems. Subsection 3.4.3 therefore investigates common used metaheuristics for the simultaneous scheduling and staffing. SA was most suitable for the C2Pa problem since SA outperforms the other metaheuristics in both computational time as performance.

At last, we deal with multi-objectiveness. There are two ways of dealing with multi-objectiveness: reducing the MOP to a single-objective problem or consider all objectives at the same time. Reducing the MOP to a single-objective problem is the most suitable for the C2Pa problem since the original SA requires a single objective function to work. Reducing the MOP to a single-objective function can be done by criterion-based methods or scalarization. Companies with C2Pa problems want a MOP method that is easy to use and understand, preferably not computational intense, and that allows trade-offs. Scalarization fits these criteria the best since they are relatively easy to understand and implement due to the single solution, allows the decision-maker to express their preferences and trade-offs between different objectives using weights, and has comparable performance with other multi-objective methods (Giagkiozis and Fleming, 2015).

To choose the most suitable scalarization method we first have to understand the wishes of the company dealing with the C2Pa problem regarding the C2Pa KPIs. Having target ranges instead of target values is desirable due to additional flexibility and extra optimization guidance these ranges bring for optimally scheduling and allocating resources. Take for example the consultant-to-project utilization KPI. A consultant with an management analyst job position should be staffed at least 90% of the consultant's working hours to generate enough income for the company, however, 100% is desired due to utilization losses between consecutive projects (Subsection 2.4.3). Therefore the company could state that the utilization KPI range is between 90% and 100% while the "higher the better" applies within this range because this generates more income. From the scalarization methods only the revised MCGP could deal with these wishes. We therefore model the C2Pa problem as the revised MCGP. Chapter 4 uses these findings for creating the modelling approach.

4 MODELLING APPROACH

This chapter answers the research question: ”What is a good modelling approach for the C2Pa problem?”. We describe the modelling approach by elaborating on the model requirements of the C2Pa problem in Section 4.1 and by providing the MILP model in Section 4.2. We conclude this chapter in Section 4.3. The most suitable problem base is the simultaneous multi-project scheduling and multi-skill staffing of Heimerl and Kolisch (2010a) (Section 3.2). This model includes the required multi-project and multi-skill case, time windows, and employee availability. Other than Heimerl and Kolisch (2010a), we do not consider external resources, overtime, and heterogeneous and static efficiency. We also extend the model of Heimerl and Kolisch (2010a) with several KPIs, constraints, and parameters. Furthermore, we deal with the multi-objectiveness by implementing a revised MCGP model in the MILP model (Chang, 2008).

4.1 Problem

This section explains the model requirements of the C2Pa problem. Subsection 4.1.1 gives the problem description of the C2Pa problem. Subsection 4.1.2 gives the objectives of the C2Pa problem. Subsection 4.1.3 gives the constraints of the C2Pa problem.

4.1.1 Problem description

The C2Pa problem is a simultaneous multi-project scheduling and assignment problem that matches multi-skilled consultants to required project skills. The project set consists of P independent projects with index p. The consultant set consists of I independent consultants with index i. The skill set consists of S required project skills with index s. Furthermore, the C2Pa problem has a time horizon of T. The index for time is t.

Consultants
Consultant i has a skill set with skill levels $csl_{s,i}$ and satisfaction $css_{s,i}$ for working and/or developing on the project skill s. Appendix table B.1 defines the skill level scale, which reaches from 0 (no experience) until 3 (expert experience). Appendix table B.2 defines the satisfaction scale, which reaches from 1 (extremely dissatisfied) until 10 (extremely satisfied). Furthermore, consultant i has an hourly cost c_i and has limited net available working hours that cannot be exceeded and are time dependent. $NH_{i,t}$ represents the net available working hours of consultant i at time t. $NH_{i,t}$ equals the working hours for consultant i at time t ($WH_{i,t}$) minus the assigned projects, trainings, and holidays.

Projects
Projects require one, or more consultants. We call this the project team. m_p represents the number of team members of project p. There is always one consultant assigned per team member role m and the consultant assigned to the team member role stays assigned to this role until project completion. The project hours per time period per team member are $PH_{p,m}$. To be able to process the projects, the C2Pa model assigns to each required project skill one

of the consultants of the project team. The duration of a project is pt_p. Each project has a starting time window in which the project must start to ensure that the project is completed in time. ES_p is the earliest start time, LS_p is the latest start time, and LF_p is the latest finish period where $LF_p = LS_p + pt_p - 1$. Moreover, projects have varying priorities, pv_p, due to relationships with clients, company strategy (e.g. target markets), and the difference between internal and goodwill projects versus client projects. At last, every project has an engagement manager who manages the project and the stakeholders. The EM is a consultant, however, the EM is not working on the required project skills. The activies of the EM are outside the scope of the C2Pa model.

Decision variables
The C2Pa model has three decision variables: $x_{i,p,t,m,s}$, $u_{p,t}$, and ap_p. $x_{i,p,t,m,s}$ is the binary assignment decision variable that equals 1 in case consultant i is assigned to team member slot m and skill s of project p at time t, and 0 otherwise. Note that assigning consultants to required project skills results in the allocation of these consultants to the project's team member slots as well. $u_{p,t}$ is the binary scheduling decision variable for setting the project start time and equals 1 in case project p starts at time t and 0 otherwise. At last, we have ap_p. ap_p is the project declining binary decision variable that equals 1 in case project p is accepted, and 0 otherwise. A project is only declined in case accepting the project leads to an infeasible solution.

Objective
The goal of the C2Pa problem is to maximize the *consultant-to-project utilization KPI*, minimize the *hourly assignment cost KPI*, maximize the *consultant satisfaction KPI*, and to bring the *C2Pa skill match KPI* as close to zero as possible. Subsection 4.1.2 describes each KPI in detail.

Assumptions
To build the multi-objective optimization C2Pa model for the above-described C2Pa problem, we use the following assumptions:

- The project hours per time period per team member ($PH_{p,m}$) remains constant during project duration. A consultant's skill level ($csl_{s,i}$) therefore does not influence the project's duration, the time it takes to perform a skill, or the project hours per time period per team member.
- In case multiple consultants are assigned to one project, the number of project skills assigned to each team member are based on the proportion of project hours the team member works on the project ($st_{p,m}$).
- Each required project skill yields an equal amount of chargeable hours ($CH_{p,t,s}$) in case of a client project and non chargeable hours ($NCH_{p,t,s}$ in case of a beach project, of the total project hours per time period for the project. In other words, $NCH_{p,t,s}$ or $CH_{p,t,s}$ is the same for every s at project p for all t.
- Projects must proceed without interruption with the same consultants fulfilling the same roles and skills throughout project duration.
- Performing the EM role takes a predetermined hours per time period (emh) and remains the same throughout the project duration.
- In case the project is accepted, each project skill is performed by one of the project's team members
- Projects consist of maximal 5 team members (excluding EM)

- The consultant's satisfaction for working on a skill ($css_{s,i}$) remains constant during a run of the C2Pa model.

4.1.2 Problem objectives

The C2Pa problem's KPIs are to maximize the *consultant-to-project utilization*, minimize the *consultant-to-project assignment cost*, maximize the *consultant satisfaction*, and to bring the *C2Pa skill match* as close to zero as possible. This subsection first discusses the KPIs independently, and afterwards provides the objective function, which aggregates the KPIs into one single objective.

Consultant-to-project utilization KPI

Equation 4.1 calculates the average consultant-to-project utilization rates per consultant. We base the consultant-to-project utilization KPI on the efficiency of the workforce KPI of Zabihi et al. (2019). Recall that the consultant-to-project utilization KPI keeps track of the percentage consultants work on client project(s). We calculate the utilization per consultant as the sum over all chargeable project hours of the consultant divided by the product of the sum over all working hours of the consultant ($WH_{i,t}$) and the time horizon (T). Chargeable project hours are the sum of three sources: allocated by the C2Pa model ($CH_{t,p,s} \cdot x_{i,p,t,m,s}$), already assigned project hours ($WH_{i,t} - NH_{i,t}$), and em hours ($emh \cdot em_{i,p} \cdot pd_{p,t}$). The already assigned hours are the working hours minus the net available hours. The net available hours are the total working hours of a consultant in the same period minus the time working for a client, education hours, and excused leaving hours like vacation. The consultant-to-project utilization KPI makes use of the following auxiliary variables: $pd_{p,t}$, $d^{+}_{i,util}$, $d^{-}_{i,util}$, and $y_{i,util}$. $pd_{p,t}$ is the binary auxiliary variable that equals 1 in case project p is in execution at time t and 0 otherwise. We include $pd_{p,t}$ to make sure that the hours for performing the EM role are only taken into consideration if the project is in execution. We compare the result of the consultant-to-project utilization KPI with a continuous variable in the aspiration level interval range of this KPI ($y_{i,util}$), negative deviations are captured in $d^{-}_{i,util}$ while positive deviations are captured in $d^{+}_{i,util}$. The higher this KPI the better, with an upperbound value for the aspiration level interval range of 100%. The current value of this KPI as well as the lowerbound aspiration level interval range value (norm) can be seen in Table 2.2.

$$\text{Avg. utilization per consultant} = \frac{\sum_{p=1}^{P}\sum_{t=0}^{T}(\sum_{m=1}^{m_p}\sum_{s=1}^{S} CH_{t,p,s} \cdot x_{i,p,t,m,s}) + WH_{i,t} - NH_{i,t} + emh \cdot em_{i,p} \cdot pd_{p,t}}{(\sum_{t=1}^{T} WH_{i,t}) \cdot T} \cdot 100 \tag{4.1}$$
$$-d^{+}_{i,util} + d^{-}_{i,util} = y_{i,util} \quad \forall i$$

Hourly cost of assigned consultants KPI

The hourly cost of assigned consultants KPI (Equation 4.2) calculates average cost per hour of assignment. We base the hourly cost of assigned consultants KPI on the labor costs KPI of Heimerl and Kolisch (2010a). This KPI takes the consultant's hourly cost (c_i) into account in case the consultant is assigned to project skill(s) ($x_{i,p,t,m,s} = 1$). The KPI sums the cost of all assignments and divides this sum by the total project hours of the accepted projects (TPT). The result of this KPI is therefore the weighted average hourly cost of assigned consultants. In order to formulate the consultant weighted average hourly cost of assigned consultants KPI calculation within the constraints of the MILP model (maintaining linearity), we replace the denominator variable TPT in the division with its maximum achievable value TPT_{max}. TPT_{max} represents the total project duration in case all projects are accepted in the planning horizon. This replacement allows us to maintain linearity in the model since TPT_{max} is not dependent on ap_p while still capturing the essence of the weighted average hourly cost of assigned consultants KPI. Since TPT_{max} remains constant during the optimization, this does not influence the optimization process (since all variable settings deal with the same TPT_{max}). After solving the MILP model, we recalculate the weighted average hourly cost of assigned consultants KPI using TPT to ensure the accuracy of our results. The weighted average hourly cost of assigned consultants is compared to the aspiration level interval range of the cost KPI. In case there are negative deviations between the total cost of assigned consultants and the continuous variable in the aspiration level interval range of the cost KPI (y_{cost}), these are captured in d^-_{cost}. The positive deviations are captured in d^+_{cost}. This KPI has an target level of €127,- (hourly cost of the Consultant job position), but the lower the better. The lowerbound for this aspiration level is therefore €115,- (hourly cost for the lowest job position, Management Analyst).

$$\text{Weighted average hourly assignment cost } = \frac{\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{t=ES_p}^{LF_p}\sum_{m=1}^{m_p}\sum_{s=1}^{S} c_i \cdot x_{i,p,t,m,s}}{TPT} - d^+_{cost} + d^-_{cost} = y_{cost} \tag{4.2}$$

Consultant satisfaction KPI

Equation 4.3 calculates the consultant satisfaction KPI by summing the satisfaction rate ($css_{s,i}$) of the assigned consultant ($x_{i,p,t,m,s} = 1$) for each project skill over all consultants over all projects over all project execution time over all skills over all team members. This sum is then divided by the total number of required skills of all accepted projects in the planning horizon (TS). In this way the average satisfaction of all assignments for all employees is expressed as a value between 1 and 10. We base the consultant satisfaction KPI on the salesmen satisfaction KPI of Abboud et al. (1998). In order to formulate the consultant satisfaction KPI calculation within the constraints of the MILP model (maintaining linearity), we replace the denominator variable TS in the division with its maximum achievable value TS_{max}. TS_{max} represents the total number of required skills in case all projects in the planning horizon are accepted. This replacement allows us to maintain linearity in the model since TS_{max} is not dependent on ap_p while still capturing the essence of the consultant satisfaction KPI. Since TS_{max} remains constant during the optimization, this does not influence the optimization process (since all variable settings deal with the same TS_{max}). After solving the MILP model, we recalculate the consultant satisfaction KPI using TS to ensure the accuracy of our results. The consultant satisfaction is compared to the aspiration level interval range of the consulant satisfaction KPI. In case there are negative deviations between the consultant satisfaction of assigned consultants and the continuous variable in the aspiration level interval range of the consultant KPI (y_{satis}), these are captured in d^-_{satis}. The positive deviations are captured in d^+_{satis}. The norm (and lowerbound value of the aspiration level) of this KPI is 6 (out of 10), but the higher this KPI the better. The upperbound value for the aspiration level interval range is 10.

$$\text{Total consultant satisfaction} = \frac{\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{t=ES_p}^{LF_p}\sum_{m=1}^{m_p}\sum_{s=1}^{S} x_{i,p,t,m,s} \cdot css_{s,i}}{TS} - d^+_{satis} + d^-_{satis} = y_{satis} \tag{4.3}$$

C2Pa skill match KPI

Since we cannot measure the quality the assigned consultant is going to deliver during the project, we decide to evaluate the quality of the match by assessing the match between the consultants' skills and competences with respect to the project's required skills and competences. We evaluate the match by subtracting the project's skill level from the consultant's skill level. Hence, the higher this KPI the higher the chance that the consultant delivers better quality for the client. However, systematically assigning overqualified consultants to projects is also not good. The assigned consultants might become bored and disengaged. For BE NL this could lead to resource misallocation since the project could also be done by less experienced consultants, leaving the experienced consultants for the more difficult projects.

Equation 4.4 calculates the C2Pa skill match. We base the C2Pa skill match KPI on the quality KPI of Chen et al. (2020). We calculate the skill match by subtracting the required project skill level ($psl_{s,p}$) from the consultant's skill level ($csl_{s,i}$) of the same skill. In case of underqualification ($psl_{s,p} > csl_{s,i}$), the skill match for that specific skill becomes negative. While in case of qualification ($psl_{s,p} = csl_{s,i}$), the skill match for that specific skill is 0. The other option is overqualification ($psl_{s,p} < csl_{s,i}$), the skill match for that specific skill is then positive. If we calculate for both the overqualification and underqualification the skill match in the same way, this will mean that in case we have two skills were one is overqualified by two levels, and the other is underqualified by two levels the overal skill match would be 0 which would mean that the consultant qualifies (total skill match of 0). In the C2Pa problem, a consultant who does not have underqualification or overqualification is a better match than a consultant who has overqualification on half of the skills and underqualification on the other half of the skills. However, if we calculate both the overqualification and underqualification for the skill match in the same way, both situations yield a skill match of 0 which means that both solutions are equal. This is not desired and we, therefore, decide to penalize underqualification more severely by squaring the consultant's skill level and project skill level before subtracting them. The reason why we choose to use a squared value is because larger differences between required skill levels and consultant's skill level (could indicate mismatch) are penalized harder than small skill level deviations for underqualification. Furthermore, a squared underqualification prevents equal overqualification for compensating the equal underqualification.

Moreover, we add the project priority value (Subsection 2.4.3). Since we have two ways of calculating the underqualification and overqualification, we introduce two binary parameters ($q_{p,s,i}$ and $w_{p,s,i}$) to make sure the right calculation. $q_{p,s,i}$ equals 1 in case there is underqualification and 0 otherwise. While $w_{p,s,i}$ equals 1 in case of overqualification and 0 otherwise. At last, to make sure that the skill match is calculated for all consultants that are assigned to team member roles and skills of projects over the entire planning horizon, we sum over time periods, team members, and project skills. The norm of the C2Pa skill match KPI equals 0 and there is no aspiration level interval. The upper and lowerbound value of the aspiration level interval are therefore equal to the norm making $y_{i,p,match}$ always equal to 0. $d^+_{i,p,match}$ therefore measures the positive differences between the skill match and 0, and $d^+_{i,p,match}$ the negative differences between the skill match and 0.

$$\text{Skill match per project per consultant} = \sum_{t=ES_p}^{LF_p} \sum_{m=1}^{m_p} (\sum_{s=1}^{S} (csl^2_{s,i} - psl^2_{s,p}) \cdot q_{p,s,i} + \\ (csl_{s,i} - psl_{s,p}) \cdot w_{p,s,i}) \cdot pv_p \cdot x_{i,p,t,m,s} - d^+_{i,p,match} + d^-_{i,p,match} = y_{i,p,match} \quad \forall i,p \tag{4.4}$$

Calculation of deviations between the KPIs and the aspiration levels

We already described the deviations to the KPI target levels (d), however, the deviations between the KPI and the aspiration level (e) are not described yet. Equation 4.5 shows the calculation of the deviation between the continuous variable that represents a value in the aspiration level interval range of the hourly cost of assigned consultants KPI (y_{cost}) and the lowerbound of the hourly cost of assigned consultants KPI aspiration level interval range. Equation 4.6 shows the interval range for the hourly cost KPI. Equation 4.7 shows the calculation of the devation between the continuous variable that represents a value in the aspiration level interval range of the consultant-to-project utilization KPI for consultant i ($y_{i,util}$) and the upperbound of the consultant-to-project utilization KPI aspiration level interval range. Equation 4.8 shows the interval range for the assignment cost KPI. Equation 4.9 shows the calculation of the deviation between the continunous variable that represents a value in the aspiration level interval range of the consultant satisfaction KPI (y_{satis}) and the lowerbound of the consultant satisfaction KPI aspiration level interval range. Equation 4.10 shows the interval range for the assignment cost KPI. The C2Pa skill match KPI does not have an apsiration level interval range and is therefore not included.

$$y_{cost} - e^{+}_{cost} + e^{-}_{cost} = 0 \tag{4.5}$$

$$115 \leq y_{cost} \leq 127 \tag{4.6}$$

$$y_{i,util} - e^{+}_{i,util} + e^{-}_{i,util} = 100 \quad \forall i \tag{4.7}$$

$$\begin{aligned} 90 \leq y_{i,util} \leq 100 \quad &\text{(in case consultant } i \text{ is } MA) \\ 80 \leq y_{i,util} \leq 100 \quad &\text{(in case consultant } i \text{ is } C) \\ 75 \leq y_{i,util} \leq 100 \quad &\text{(in case consultant } i \text{ is } SC) \\ 65 \leq y_{i,util} \leq 100 \quad &\text{(in case consultant } i \text{ is } M) \end{aligned} \tag{4.8}$$

$$y_{satis} - e^{+}_{satis} + e^{-}_{satis} = 10 \tag{4.9}$$

$$6 \leq y_{satis} \leq 10 \tag{4.10}$$

Objective function
The objective function (4.11) balances the goals encountered in a C2Pa problem by minimizing the normalized deviations between the KPI values and the norms and multiply this normalized deviation by the weights. The objective function uses deviations to the target level and aspiration levels of the KPIs instead of KPI values as derived from the MCGP model (Chang, 2008). We normalize the deviations to prevent one deviation dominating the optimal solution due to a different magnitude (scale). For example, the consultant satisfaction KPI has a value between 0 and 10, while the consultant-to-project utilization KPI has a value between 0 and 100. The most suitable normalization method for the C2Pa problem is the Chebychev normalization (Appendix E). The Chebyshev normalization involves dividing each element by the largest absolute value, ensuring that the range of normalized values is [-1, 1]. Since we capture the negative deviations as a positive number in the negative deviation variable, we do not encounter negative values meaning that the Chebyshev normalization always lead to a value of [0, 1]. Advantages of using the Chebyshev normalisation is that this normalization ensures that extreme values have a significant impact on the normalized values and tends to be robust to outliers. These characteristics are important for the C2Pa problem due to the varying magnitudes and variations between the KPI deviations.

Moreover, note that the model calculates the deviations attached to the consultant-to-project utilization per consultant instead of for all consultants. The reason for this is that in the C2Pa application area, companies have for each consultant an individual consultant-to-project utilization target level. Since not all deviation KPIs are calculated for each consultant and then summed, we use the average deviation to the consultant-to-project utilization target level KPI for all consultants.

We want the skill match KPI to be independent of the project time to ensure good quality for each project, instead of focusing more on the longer projects. Furthermore, the skill match KPI should be considered per consultant to make sure that the model does not compensate the skill match between consultants in a consultant. To make the skill match consultant and project dependent we make the skill match deviation constraint a two-index variable and sum over the projects and consultants to make sure we still calculate the overall skill match. However, since not all KPIs are calculated as the sum for the projects and the consultants, we calculate the average value by dividing by $P \cdot I$. To be able to make the skill match KPI time independent we need to multiply the normalization factor with the project duration.

At last, we add a penalty term for the declined projects to the C2Pa model's objective. The declined project penalty term consists of the sum of the multiplication of the priority value of the project and the weight for declining a project in case the project is declined, for all projects. However, since not all objective terms are calculated as the sum over all projects, we calculate the average penalty term over all projects by dividing by P.

$$\text{Minimize}$$
$$\begin{gathered}
w^+_{cost} \cdot \frac{d^+_{cost}}{TotMaxAbsCost} + w^-_{cost} \cdot \frac{d^-_{cost}}{TotMaxAbsCost} + \alpha^+_{cost} \cdot \frac{e^+_{cost}}{TotMaxAbsCost} + \alpha^-_{cost} \cdot \frac{e^-_{cost}}{TotMaxAbsCost} \\
+\frac{1}{I} \cdot \sum_{i=1}^{I} \left(w^+_{util} \cdot \frac{d^+_{i,util}}{TotMaxAbsUtil} + w^-_{util} \cdot \frac{d^-_{i,util}}{TotMaxAbsUtil} + \alpha^+_{util} \cdot \frac{e^+_{i,util}}{TotMaxAbsUtil} + \alpha^-_{util} \cdot \frac{e^-_{i,util}}{TotMaxAbsUtil} \right) \\
+w^+_{satis} \cdot \frac{d^+_{satis}}{TotMaxAbsSatis} + w^-_{satis} \cdot \frac{d^-_{satis}}{TotMaxAbsSatis} + \alpha^+_{satis} \cdot \frac{e^+_{satis}}{TotMaxAbsSatis} + \alpha^-_{satis} \cdot \frac{e^-_{satis}}{TotMaxAbsSatis} \\
+\frac{1}{P} \cdot \frac{1}{I} \cdot \sum_{p=1}^{P} \sum_{i=1}^{I} \left(w^+_{match} \cdot \frac{d^+_{i,p,match}}{TotMaxAbsMatch \cdot pt_p} + w^-_{match} \cdot \frac{d^-_{i,p,match}}{TotMaxAbsMatch \cdot pt_p} \right) \\
+\frac{1}{P} \cdot \sum_{p=1}^{P} w_{decline} \cdot pv_p \cdot (1 - ap_p)
\end{gathered} \tag{4.11}$$

4.1.3 Constraints C2Pa problem

The C2Pa problem deals with the following constraints:

Project declined constraint
With use of three constraints, we make sure that the model avoids assigning consultants to project skills in case a project is declined: one constraint for binary decision variable $x_{i,p,t,m,s}$, one constraint for binary decision variable $u_{p,t}$, and one constraint for binary decision variable $pd_{p,t}$. Constraint 4.12 makes sure that no consultants are assigned to any team member roles and skills of the projects at any time. Constraint 4.13 makes sure that there is no starting time for a project in case the project is declined. Constraint 4.14 makes sure that the project is not executed ($pd_{p,t} = 0$) in case the project is declined. In Constraint 4.14 we multiply the project duration (pt_p) to the decision variable if the project is declined or not to make sure that in case the project is not declined that the project execution variable can be 1 for the entire project duration.

$$x_{i,p,t,m,s} \leq ap_p \quad \forall i, p, t, m, s \tag{4.12}$$

$$\sum_{t=ES_p}^{LS_p} u_{p,t} = ap_p \quad \forall p \tag{4.13}$$

$$\sum_{t=1}^{T} pd_{p,t} \leq pt_p \cdot ap_p \quad \forall p \tag{4.14}$$

Project execution constraint

To make sure that the C2Pa model only assigns consultants during project execution to all required team member roles and project skills, we introduce two constraints. Constraint 4.15 makes sure that the project execution starts ($pd_{p,t} = 1$) when the decision variable ($u_{p,t}$) equals 1 and ends with being 1 when the project duration is over ($t = t + pt_p$). Constraint 4.16 makes sure that all project team members are assigned to a number of project skills based on the proportion of project hours they work ($st_{p,m}$). Since the sum over $st_{p,m}$ for the project team members equal the total number of required project skills, we ensure all project skills are assigned. Furthermore, this constraint ensures that all team members roles are filled in case a project is accepted, since $pd_{p,t} = 1$ during execution of the project.

$$pt_p \cdot u_{p,t} \leq \sum_{t1=t}^{min(t+pt_p,T)} pd_{p,t1} \quad t \in \{ES_p, ..., LS_p\} \text{ and } \forall i, p, m, s \tag{4.15}$$

$$\sum_{i=1}^{I} \sum_{s=1}^{S} x_{i,p,t,m,s} = st_{p,m} \cdot pd_{p,t} \quad \forall p, t, m \tag{4.16}$$

One consultant per team member role constraint

A team member role can only be performed by one consultant and this consultant should remain assigned until the project is completed. We use three constraints for enforcing this behaviour for the C2Pa model, and introduce auxiliary variable $z_{i,p,m}$. $z_{i,p,m}$ is a binary variable that equals 1 in case consultant i is assigned to team member m of project p. Constraint 4.17 makes sure that only 1 consultant can be assigned per project and team member role. Constraint 4.18 makes sure that only 1 team member can be assigned per project and consultant. At last, we have Constraint 4.19 to make sure that the model only assigns 1 consultant per team member m of project p. The constraint ensures that $x_{i,p,t,m,s}$ can only be assigned 1 in case $z_{i,p,m}$ equals 1.

$$\sum_{i=1}^{I} z_{i,p,m} \leq 1 \quad \forall p, m \tag{4.17}$$

$$\sum_{m=1}^{m_p} z_{i,p,m} \leq 1 \quad \forall p, i \tag{4.18}$$

$$x_{i,p,t,m,s} \leq z_{i,p,m} \quad \forall i, p, t, m, s \tag{4.19}$$

Net available hours constraint

The net available hours constraint (Constraint 4.20) ensures that consultant i does not work more than the consultant has time available in time period t ($NH_{i,t}$). Note that this constraint enables consultants to work simultaneously on multiple projects in case the consultants' availability allows this. This is the case since we sum for consultant i all chargeable ($CH_{t,p,s}$) and nonchargeable hours ($NCH_{t,p,s}$) for skill s of project p at time t to which the consultant is assigned to ($x_{i,p,t,m,s}$). Moreover, we add the EM hours.

$$\sum_{p=1}^{P}\sum_{m=1}^{m_p}\sum_{s=1}^{S}\left(CH_{t,p,s}\cdot x_{i,p,t,m,s}+\frac{emh\cdot em_{i,p}\cdot pd_{p,t}}{m_p\cdot S}+NCH_{t,p,s}\cdot x_{i,p,t,m,s}\right) \leq NH_{i,t} \quad \forall i,t \tag{4.20}$$

One team member per required project skill
Constraint 4.21 makes sure that only 1 team member per required project skill can be assigned.

$$\sum_{i=1}^{I}\sum_{m=1}^{m_p} x_{i,p,t,m,s} \leq 1 \quad \forall p,t,s \tag{4.21}$$

Starting time window constraint
Constraint 4.22 makes sure that the C2Pa model cannot be assigned outside the project time window.

$$x_{i,p,t,m,s} \leq 0 \quad t \notin \{ES_p,...,LF_p\} \text{ and } \forall i,p,m,s \tag{4.22}$$

Only assign to required project skills constraint
Constraint 4.23 makes sure that the C2Pa model cannot assign to project skills not required by the project. The avoids extra assignments of consultants to irrelevant skills to improve KPIs.

$$x_{i,p,t,m,s} \leq rs_{s,p} \quad \forall i,p,t,m,s \tag{4.23}$$

Same skill assignment during project duration constraint
Constraint 4.24 and 4.25 make sure that the same project skills are assigned to the same consultant (team member) during project duration. $v_{i,p,m,s}$ is a binary variable that equals 1 in case consultant i is assigned to team member role m and skill s of project p. Constraint 4.24 makes sure that for all project and skills only 1 consultant (team member) can perform the project skill independent of the time. Constraint 4.25 makes sure that this behaviour applies to $x_{i,p,t,m,s}$ as well.

$$\sum_{i=1}^{I}\sum_{m=1}^{m_p} v_{i,p,m,s} = ap_p \quad \forall p,s \tag{4.24}$$

$$x_{i,p,t,m,s} = v_{i,p,m,s} \quad \forall i,p,t,m,s \tag{4.25}$$

Sign constraints
The sign constraints (Constraint 4.26 until 4.34) restrict the feasible solution space, guide the behaviour of variables in mathematical models, or represent real-world limitations in certain context.

$$x_{i,p,t,m} \in \{0,1\} \tag{4.26}$$

$$u_{p,t} \in \{0,1\} \tag{4.27}$$

$$ap_p \in \{0, 1\} \quad (4.28)$$

$$pd_{p,t} \in \{0, 1\} \quad (4.29)$$

$$v_{i,p,m,s} \in \{0, 1\} \quad (4.30)$$

$$z_{i,p,m} \in \{0, 1\} \quad (4.31)$$

$$TPT \geq 0 \quad (4.32)$$

$$TS \geq 0 \quad (4.33)$$

$$d_k^+, d_k^-, e_k^+, e_k^- \geq 0 \quad (4.34)$$

4.2 Model description

We can now model the following mixed integer linear programming (MILP) model:

Indices	**Description**
i	Consultant index i with $i = 1, \ldots, I$
m	Team member index m with $m = 1, \ldots, m_p$
p	Project index p with $p = 1, \ldots, P$
s	Skill index s with $s = 1, \ldots, S$
t	Time index t with $t = 1, \ldots, T$

Parameters	**Description**
α^+_{cost} and α^-_{cost}	Positive and negative weight attached to the normalized sum of deviations of e^+_{cost} and e^-_{cost}
α^+_{util} and α^-_{util}	Positive and negative weight attached to the normalized sum of deviations of e^+_{util} and e^-_{util}
α^+_{satis} and α^-_{satis}	Positive and negative weight attached to the normalized sum of deviations of e^+_{satis} and e^-_{satis}
c_i	Hourly cost parameter for assigning consulant i to a project based on the consultant's job position (see Table 2.1)
$CH_{t,p,s}$	Chargeable hours parameter for required skill s of project p at period t
$csl_{s,i}$	Consultant i's skill level parameter for skill s (according to the skill level range as specified in Table B.1)
$css_{s,i}$	Consultant i's skill satisfaction parameter for skill s (according to the satisfaction scale as specified in Table B.2)
$em_{i,p}$	Binary parameter that equals 1 in case consultant i is working as EM on project p and 0 otherwise.
emh	Parameter that represents the hours an EM is working as EM per project per week.
ES_p	Project p's earliest start time parameter
I	Number of consultants parameter

Parameters	Description
LF_p	Project p's latest finish time where $LF_p = LS_p + pt_p - 1$
LS_p	Project p's latest start time parameter
m_p	Number of team members in project p parameter
$NCH_{t,p,s}$	Non-chargeable hours parameter for required skill s of project p at period t
$NH_{i,t}$	Net hours parameter of consultant i in period t
P	Number of projects parameter
$PH_{p,m}$	Number of project hours for team member m of project p for every t during the project. $PH_{p,m}$ remains constant during the project (does not change).
$psl_{s,p}$	Project p's skill requirement level parameter for skill s (according to the skill levels range as specified in Table B.1)
pt_p	Project p's processing time parameter
pv_p	Priority value parameter for project p according to (Subsection 2.4.3)
$q_{p,s,i}$	Binary parameter underqualification for skill s for consultant i on project p. $q_{p,s,i}$ = $\begin{cases} 1\, if\, psl_{s,p} \geq csl_{s,i} \\ 0\, otherwise \end{cases}$
$rs_{p,s}$	Binary parameter if skill s is required for project p. $rs_{p,s}$ = $\begin{cases} 1\, if\, psl_{s,p} \geq 1 \\ 0\, otherwise \end{cases}$
S	Number of skills parameter
$st_{p,m}$	Number of required skills of project p that are assigned to team member m parameter.
T	Number of time in planning horizon parameter
$TotMaxAbsCost$	The total maximum absolute hourly cost is a parameter that represents the maximum absolute value of the hourly cost of assigned consultants KPI. The maximum absolute cost value is 165.
$TotMaxAbsMatch$	The total maximum absolute skill match is a parameter that represents the maximum absolute value of the C2Pa skill match KPI. The maximum absolute C2Pa skill match value is reached when a project requires a skill at expert level (3) while the consultant does not have this skill (0). The skill match for the required project skill would then become $0^2 - 3^2 = 9$. Since in the absolute worst case this could be required for all project skills and all projects we multiply this value by the number of projects P and the number of skills S. Therefore $TotMaxAbsMatch = (\max(PSL_{s,p}))^2 \cdot P \cdot S$.
$TotMaxAbsSatis$	The total maximum absolute satisfaction is a parameter that represents the maximum absolute value of the consultant satisfaction KPI. The maximum satisfaction that a consultant can give a certain skill is 10. Therefore $TotMaxAbsSatis = 10$.
$TotMaxAbsUtil$	The total maximum absolute consultant-to-project utilization is a parameter that represents the maximum absolute value of the consultant-to-project utilization KPI. The maximum utilization that a consultant can achieve is 100 percent. Therefore $TotMaxAbsSatis = 100$.
TPT_{max}	Parameter that represents the total project hours for all projects in the planning horizon.
TS_{max}	Sum of the number of required skills parameter for all projects in the planning horizon.

Parameters	Description
$w_{p,s,i}$	Binary parameter overqualification for skill s for consultant i on project p. $w_{p,s,i}$ = $\begin{cases} 1\, if\; csl_{s,i} \geq psl_{s,p} \\ 0\; otherwise \end{cases}$
$w_{decline}$	Weight attached to the normalized penalty factor for declining a project
w^+_{cost} and w^-_{cost}	Positive and negative weight attached to normalized deviations of the hourly cost of assigned consultants goal (d^+_{cost} and d^-_{cost})
w^+_{util} and w^-_{util}	Positive and negative weight attached to normalized deviations of the total consultant-to-project utilization rates goal (d^+_{util} and d^-_{util})
w^+_{satis} and w^-_{satis}	Positive and negative weight attached to normalized deviations of the consultant satisfaction rates goal (d^+_{satis} and d^-_{satis})
w^+_{match} and w^-_{match}	Positive and negative weight attached to normalzied deviations of the C2Pa skill match goal (d^+_{match} and d^-_{match})
$WH_{i,t}$	Parameter that represents the working hours of consultant i at time t

Decision variables	Description
$u_{p,t}$	Binary decision variable that equals 1 if project p starts at time t and 0 otherwise.
$x_{i,p,t,m,s}$	Binary decision variable that equals 1 in case consultant i is assigned to team member slot m and skill s of project p at time t, and 0 otherwise.
ap_p	Binary decision variable that equals 1 in case project p is accepted (all team member slots are assigned to consultants), and 0 otherwise.

Auxiliary variables	Description
d^+_{cost} and d^-_{cost}	Positive and negative deviation variable between the hourly cost of assigned consultants KPI and the continuous variable that represents a value in the aspiration level interval range
$d^+_{i,util}$ and $d^-_{i,util}$	Positive and negative deviation variable between the consultant-to-project utilization rates KPI and the continuous variable that represents a value in the aspiration level interval range for consultant i
$d^+_{i,p,match}$ and $d^-_{i,p,match}$	Positive and negative deviation variable between the C2Pa skill match KPI and the continuous variable that represents a value in the aspiration level interval range for consultant i and project p
d^+_{satis} and d^-_{satis}	Positive and negative deviation variable between the consultant satisfaction rates KPI and the continuous variable that represents a value in the aspiration level interval range
e^+_{cost} and e^-_{cost}	Positive and negative deviation variable between the continuous variable that represents a value in the aspiration level interval range and the desired minimum or maximum aspiration level of the hourly cost of assigned consultants KPI

Auxiliary variables	Description
$e^+_{i,util}$ and $e^-_{i,util}$	Positive and negative deviation variable between the continuous variable that represents a value in the aspiration level interval range and the desired minimum or maximum aspiration level of the consultant-to-project utilization rates KPI for consultant i
e^+_{satis} and e^-_{satis}	Positive and negative deviation variable between the continuous variable that represents a value in the aspiration level interval range and the desired minimum or maximum aspiration level of the consultant satisfaction rates KPI
$pd_{p,t}$	Binary auxiliary variable that equals 1 in case project p is in execution at time t and 0 otherwise
TPT	Auxiliary variable that represents the total project hours for all accepted projects in the planning horizon.
TS	Auxiliary variable that represents the number of required skills parameter for all accepted projects in the planning horizon.
$v_{i,p,m,s}$	Binary auxiliary variable that equals 1 in case consultant i is assigned to team member role m and skill s of project p and 0 otherwise
y_{cost}	Continuous variable that represents a value in the aspiration level interval range of the hourly cost of assigned consultants KPI
$y_{i,util}$	Continuous variable that represents a value in the aspiration level interval range of the consultant-to-project utilization rates KPI for consultant i
y_{satis}	Continuous variable that represents a value in the aspiration level interval range of the consultant satisfaction rates KPI
$z_{i,p,m}$	Binary auxiliary variable that equals 1 in case consultant i is working as team member m on project p

Minimize

$$\begin{aligned}
& w^+_{cost} \cdot \frac{d^+_{cost}}{TotMaxAbsCost} + w^-_{cost} \cdot \frac{d^-_{cost}}{TotMaxAbsCost} + \alpha^+_{cost} \cdot \frac{e^+_{cost}}{TotMaxAbsCost} + \alpha^-_{cost} \cdot \frac{e^-_{cost}}{TotMaxAbsCost} \\
& + \frac{1}{I} \cdot \sum_{i=1}^{I} \left(w^+_{util} \cdot \frac{d^+_{i,util}}{TotMaxAbsUtil} + w^-_{util} \cdot \frac{d^-_{i,util}}{TotMaxAbsUtil} + \alpha^+_{util} \cdot \frac{e^+_{i,util}}{TotMaxAbsUtil} + \alpha^-_{util} \cdot \frac{e^-_{i,util}}{TotMaxAbsUtil} \right) \\
& + w^+_{satis} \cdot \frac{d^+_{satis}}{TotMaxAbsSatis} + w^-_{satis} \cdot \frac{d^-_{satis}}{TotMaxAbsSatis} + \alpha^+_{satis} \cdot \frac{e^+_{satis}}{TotMaxAbsSatis} + \alpha^-_{satis} \cdot \frac{e^-_{satis}}{TotMaxAbsSatis} \\
& + \frac{1}{P} \cdot \frac{1}{I} \cdot \sum_{p=1}^{P} \sum_{i=1}^{I} \left(w^+_{match} \cdot \frac{d^+_{i,p,match}}{TotMaxAbsMatch \cdot pt_p} + w^-_{match} \cdot \frac{d^-_{i,p,match}}{TotMaxAbsMatch \cdot pt_p} \right) \\
& + \frac{1}{P} \cdot \sum_{p=1}^{P} w_{decline} \cdot pv_p \cdot (1 - ap_p)
\end{aligned} \tag{4.35}$$

Subject to:

$$\frac{\sum_{i=1}^{I} \sum_{p=1}^{P} \sum_{t=ES_p}^{LF_p} \sum_{m=1}^{m_p} \sum_{s=1}^{S} c_i \cdot x_{i,p,t,m,s}}{TPT} - d^+_{cost} + d^-_{cost} = y_{cost} \tag{4.36}$$

$$\begin{aligned}
& \frac{\sum_{p=1}^{P} \sum_{t=0}^{T} (\sum_{m=1}^{m_p} \sum_{s=1}^{S} CH_{t,p,s} \cdot x_{i,p,t,m,s}) + WH_{i,t} - NH_{i,t} + emh \cdot em_{i,p} \cdot pd_{p,t}}{(\sum_{t=1}^{T} WH_{i,t}) \cdot T} \cdot 100 \\
& - d^+_{i,util} + d^-_{i,util} = y_{i,util} \quad \forall i
\end{aligned} \tag{4.37}$$

$$\frac{\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{t=ES_p}^{LF_p}\sum_{m=1}^{m_p}\sum_{s=1}^{S} x_{i,p,t,m,s}\cdot css_{s,i}}{TS} - d^+_{satis} + d^-_{satis} = y_{satis} \tag{4.38}$$

$$\sum_{t=ES_p}^{LF_p}\sum_{m=1}^{m_p}(\sum_{s=1}^{S}(csl^2_{s,i} - psl^2_{s,p})\cdot q_{p,s,i} + (csl_{s,i} - psl_{s,p})\cdot w_{p,s,i}) \\ \cdot pv_p \cdot x_{i,p,t,m,s} - d^+_{i,p,match} + d^-_{i,p,match} = 0 \quad \forall i,p \tag{4.39}$$

$$\sum_{p=1}^{P}\sum_{m=1}^{m_p}\sum_{s=1}^{S}\left(CH_{t,p,s}\cdot x_{i,p,t,m,s} + \frac{emh\cdot em_{i,p}\cdot pd_{p,t}}{m_p\cdot S} + NCH_{t,p,s}\cdot x_{i,p,t,m,s}\right) \\ \leq NH_{i,t} \quad \forall i,t \tag{4.40}$$

$$x_{i,p,t,m,s} \leq ap_p \quad \forall i,p,t,m,s \tag{4.41}$$

$$\sum_{i=1}^{I} z_{i,p,m} \leq 1 \quad \forall p,m \tag{4.42}$$

$$\sum_{m=1}^{m_p} z_{i,p,m} \leq 1 \quad \forall p,i \tag{4.43}$$

$$x_{i,p,t,m,s} \leq z_{i,p,m} \quad \forall i,p,t,m,s \tag{4.44}$$

$$\sum_{i=1}^{I}\sum_{m=1}^{m_p} x_{i,p,t,m,s} \leq 1 \quad \forall p,t,s \tag{4.45}$$

$$\sum_{t=ES_p}^{LS_p} u_{p,t} = ap_p \quad \forall p \tag{4.46}$$

$$x_{i,p,t,m,s} \leq 0 \quad t \notin \{ES_p,...,LF_p\} \text{ and } \forall i,p,m,s \tag{4.47}$$

$$x_{i,p,t,m,s} \leq rs_{s,p} \quad \forall i,p,t,m,s \tag{4.48}$$

$$\sum_{i=1}^{I}\sum_{s=1}^{S} x_{i,p,t,m,s} = st_{p,m}\cdot pd_{p,t} \quad \forall p,t,m \tag{4.49}$$

$$pt_p \cdot u_{p,t} \leq \sum_{t=t}^{min(t+pt_p,T)} pd_{p,t} \quad t \in \{ES_p,...,LS_p\} \text{ and } \forall i,p,m,s \tag{4.50}$$

$$\sum_{t=1}^{T} pd_{p,t} \leq pt_p \cdot ap_p \quad \forall p \tag{4.51}$$

$$\sum_{i=1}^{I}\sum_{m=1}^{m_p} v_{i,p,m,s} = ap_p \quad \forall p,s \tag{4.52}$$

$$x_{i,p,t,m,s} = v_{i,p,m,s} \quad \forall i,p,t,m,s \tag{4.53}$$

$$y_{cost} - e^+_{cost} + e^-_{cost} = 0 \tag{4.54}$$

$$y_{i,util} - e^+_{i,util} + e^-_{i,util} = 100 \quad \forall i \tag{4.55}$$

$$y_{satis} - e^+_{satis} + e^-_{satis} = 10 \tag{4.56}$$

$$x_{i,p,t,m} \in \{0,1\} \tag{4.57}$$

$$u_{p,t} \in \{0,1\} \tag{4.58}$$

$$ap_p \in \{0,1\} \tag{4.59}$$

$$pd_{p,t} \in \{0,1\} \tag{4.60}$$

$$v_{i,p,m,s} \in \{0,1\} \tag{4.61}$$

$$z_{i,p,m} \in \{0,1\} \tag{4.62}$$

$$TPT \geq 0 \tag{4.63}$$

$$TS \geq 0 \tag{4.64}$$

$$d^+_k, d^-_k, e^+_k, e^-_k \geq 0 \tag{4.65}$$

$$115 \leq y_{cost} \leq 127 \tag{4.66}$$

$$\begin{gathered} 90 \leq y_{i,util} \leq 100 \quad \text{(in case consultant } i \text{ is } MA) \\ 80 \leq y_{i,util} \leq 100 \quad \text{(in case consultant } i \text{ is } C) \\ 75 \leq y_{i,util} \leq 100 \quad \text{(in case consultant } i \text{ is } SC) \\ 65 \leq y_{i,util} \leq 100 \quad \text{(in case consultant } i \text{ is } M) \end{gathered} \tag{4.67}$$

$$6 \leq y_{satis} \leq 10 \tag{4.68}$$

4.3 Conclusion

This chapter started with describing the model requirements of the C2Pa problem. The C2Pa model requires 3 decision variables: an assignment decision variable, a scheduling decision variable, and a decline project decision variable. Furthermore, the C2Pa model has 4 objectives: consultant satisfaction, consultant-to-project utilization, hourly assignment cost, and skill match. We deal with the multiple objectives by implementing the revised MCGP of Chang (2008). In the revised MCGP the objective function is to minimize the deviations to the target level and the aspiration interval level. Target levels are the predetermined goals for each KPI (minimum desired performance). The aspiration interval level range is the range between the target level and the optimal desired performance. Furthermore, Subsection 4.1.3 elaborates on the constraints in the C2Pa problem. Combining all these elements leads to the mathematical model described in Section 4.2. We use this model in Chapter 5 to perform the experiments with.

5 MODEL RESULTS, ANALYSIS, AND VALIDATION

Chapter 4 described the modelling approach for creating the C2Pa model. This chapter uses that model to generate results, to use these results for the analysis, and to validate the model to answer the research question: ”How does the model perform for different scenarios of the C2Pa problem?”. Section 5.1 describes the experimental design of this research. Section 5.2 verifies the model. Section 5.3 validates the model. Section 5.4 analyses the performance of the model. Section 5.5 evaluates the impact of different time window sizes on the results of the C2Pa model. Section 5.6 evaluates the impact of different company sizes on the C2Pa model's computational time. Section 5.7 evaluates the impact of different organizational capabilities on the results of the C2Pa model. Section 5.8 presents the main take-aways of Chapter 5.

5.1 Experimental design

This section discusses the experimental design. Subsection 5.1.1 provides the dataset for the C2Pa model. Subsection 5.1.2 provides the experiments. We execute all experiments using a Python 3.11.5 engine on Spyder IDE version 5.4.3, on a computer with an Intel(R) Core(TM) i7-8750H CPU of 2.20GHz and 16.0 GB RAM. In Python we use the PuLP package version 2.7.0 and the Gurobi Optimizer version 11.0.0 build v11.0.0rc2.

5.1.1 Dataset

Table 5.1 shows the dataset for the C2Pa model. The input is based on data of the D&A service line of BE NL (Appendix F and G). For the experiments, we generate data instances from the dataset. This is possible since the distributions with the same setting give different values for each instance.

All weights, except the weight for declining a project, are 1. The weight for declining a project is a large number (200,000,000) since BE NL only wants to decline a project in case this leads to an infeasible solution. The normalization factors ($TotMaxAbsUtil$, $TotMaxAbsCost$, $TotMaxAbsMatch$, and $TotMaxAbsSatis$) are according to Section 4.2. The EM hours per project per week parameter (emh) equals 4 hours. We have 15 consultants (I), 9 projects (P), a planning horizon of 52 weeks (T), and 23 project skills (S).

We evenly spread the projects by generating the earliest start periods of the projects ES_p from a discrete uniform distribution between period 0 and 51 minus pt_p as inspired by Heimerl and Kolisch (2010a). There are no start time windows for the projects so $ES_p = LS_p$. Furthermore, we generate if the project is a beach request or not and the number of team members with a probability determined from the distribution of the base case parameters. One third of the projects in the D&A team is a beach request (two third a client project) and 2 out of the 9 projects has two team members (7 out of the 9 one team member).

For the other parameters, we try to fit appropriate probability distributions to capture the variability and uncertainties associated with these parameters. Our approach involves employing a goodness of fit test to identify and fit distributions that align with the observed data. Since all input values are integers and all inputs are defined as integers as well (for example skill levels are in integers) we need a discrete distribution. The Poisson distribution is the most suitable discrete distribution since we do not have trials until success (so geometric distribution not suitable), we have more than two possible outcomes (so binomial distribution not suitable either), and we want to model the parameters that occur in a fixed interval of time (planning horizon). The goodness of fit tests (Appendix I) prove that for the $csl_{s,i}$, $psl_{s,i}$, and $css_{s,i}$ the Poisson distribution is a good option, while for the pt_p and $PH_{p,m}$ the Poisson distribution is not a good option. We use truncated Poisson distributions to make sure the values stay in feasible regions ($Truncated\,Poisson(\lambda, lowerbound, upperbound)$) where λ represents the average. For pt_p and $PH_{p,m}$ we randomly generate input data from the pt_p and $PH_{p,m}$ dataset of BE NL from 2022-2023 (Appendix G).

Weights (w & α) = Appendix F.1	T = 52
$TotMaxAbsUtil$ = 100	S = 23
$TotMaxAbsCost$ = max$(c_i) \cdot 40 \cdot$ sum(pt_p)	pv_p and EM_p = Appendix F.3
$TotMaxAbsMatch$ = (max$(PSL_{s,p}))^2 \cdot P \cdot S$	$NH_{i,t} \sim$ NH (Appendix table G.3)
$TotMaxAbsSatis$ = 10	$css_{s,i} \sim$ Truncated Poisson(5.7, 0.0, 10.0)
emh = 4	$pt_p \sim$ PT (Appendix table G.2)
I = 15	$PH_{p,m} \sim$ PH (Appendix table G.1)
P = 9	$psl_{s,p} \sim$ Truncated Poisson(0.5, 0.0, 3.0)
$ES_p - LS_p = 0$	$ES_p \sim$ U[0, 52 - pt_p]
P($beach_p$ = 0) = 2/3 P($beach_p$ = 1) = 1/3	P(m_p = 1) = 7/9 P(m_p = 2) = 2/9
$csl_{s,i} \sim$ Truncated Poisson(0.8, 0.0, 3.0) in case consultant i has job position MA $csl_{s,i} \sim$ Truncated Poisson(1.3, 0.0, 3.0) in case consultant i has job position C $csl_{s,i} \sim$ Truncated Poisson(1.2, 0.0, 3.0) in case consultant i has job position SC	

Table 5.1: Dataset for the C2Pa model

5.1.2 Experiments

This subsection provides the experiments of this research. Table 5.2 shows the different scenarios for each experiment. We have 4 experiments with in total 16 scenarios. For the first experiment we run 1 instance per scenario due to time intensiveness of creating the scenario, while for the last three experiments we run 10 instances per scenario. This leads to a total of 142 runs since the total number of runs is determined by adding up the instances run for each scenario.

Experiment	**Factor(s)**	**Scenarios**	**Instance(s) per scenario**
Performance OTL vs C2Pa model	$x_{i,p,t,m,s}$ (assignment variable)	free, fixed according to Table 5.3	1
Flexible start time window of projects	LS_p–ES_p (in weeks)	0.0, 1.0, 2.0, 3.0, 4.0	10
Company size	I & P	$I = 8$ & $P = 5$, $I = 15$ & $P = 9$, $I = 23$ & $P = 14$, $I = 30$ & $P = 18$	10
Organizational capabilities	λ in $csl_{s,i}$	-0.5, 0.0, +0.5, +1.0, +1.5	10

Table 5.2: Experimental test design

Performance evaluation of the C2Pa model versus the current OTL C2Pa procedure
By comparing the outcome of the C2Pa model with the outcome of the OTL C2Pa procedure, we can benchmark the C2Pa model against the current OTL assignment procedure. This evaluation helps assessing the overall effectiveness of the C2Pa model. For the performance evaluation experiment, we have 2 scenarios: one where the C2Pa model can freely assign the decision variable $x_{i,p,t,m,s}$, and one where the C2Pa model assigns according to the decisions of the OTL (Table 5.3) to calculate the OTL's performance.

Project	$x_{i,p,t,m,s}$
2	$x_{3,2,t,0,s} = 1$ $s \in \{0, 1, 4, 15, 16\}$ and $t \in \{32, 33, 34\}$
4	$x_{12,4,t,0,s} = 1$ $s \in \{0, 11, 16\}$ and $t \in \{27, 28\}$
5	$x_{12,5,t,0,s} = 1$ $s \in \{11, 16, 19, 21\}$ and $t \in \{33\}$
6	$x_{13,6,t,0,s} = 1$ $s \in \{0, 1, 3, 8, 9\}$ and $t \in \{11\}$ $x_{1,6,t,1,s} = 1$ $s \in \{11, 12, 15, 16, 19\}$ and $t \in \{11\}$
8	$x_{12,8,t,0,s} = 1$ $s \in \{7, 14, 17, 20\}$ and $t \in \{19, 20, ..., 31\}$
0,1,3,7	all other $x_{i,p,t,m,s} = 0$

Table 5.3: OTL assignments for the base case

Impact flexibility start time windows on the solution
By varying the start time window sizes of the projects we can investigate the impact of the start time window size on the solution. These insights are valuable for companies to determine if they want to negotiate more with their clients about the flexible starting times of projects. For the start time window experiment, we have 5 scenarios: 0, 1, 2, 3, and 4 weeks. We choose to experiment with these five scenarios since the maximum feasible start time window seen in actual projects equals 4 weeks.

Usability of C2Pa model with respect to company size
By increasing the number of projects and consultants we provide insights in the usability of the C2Pa model for different company sizes. We asses the usability of the model based on the computational times involved with running the C2Pa model. For the company size experiment, we have 4 scenarios: 8 consultants and 5 projects, 15 consultants and 9 projects, 23 consultants and 14 projects, and 30 consultants and 18 projects.

Effect organizational capabilities on the solution
By using different consultant skill sets, we can see the impact of companies with better and worse skilled people on the solution. Furthermore, varying the organizational capabilities illustrates how training your employees on the skills influences the solution. For the organizational capability experiment, we have 5 scenarios varying the average skill level of a consultant (λ) of the truncated Poisson distribution with steps of 0.5 between -0.5 and +1.5. The reason for this experimental level range is because decreasing λ with 0.5 will lead to a λ value closest to 0 (lowerbound consultant skill level), while increasing λ with 1.5 will lead to a λ value closest to 3 (upperbound consultant skill level).

5.2 Model verification

To verify the correctness of the C2Pa model, we focus on optimizing one KPI at a time and compare the C2Pa model's result with manually determined values. Simplifying the model to one KPI allows thorough examination of the model's behavior and performance with respect to that single KPI and eases the calculation of the optimal value which we use to check the correctness of the model. In this way, we can verify that the C2Pa model behaves as expected and produces accurate results for each KPI. For the verification experiment (single KPI optimization) the value of the weight factors (w & α) of the chosen KPI equal 1 while the others are equal to 0. This makes sure the C2Pa model only takes the single KPI in consideration during optimization. The C2Pa problem has 4 KPIs and we therefore have 4 scenarios for the verification case. For each scenario we run 2 instances. Table 5.4 shows the results of the single KPI optimization experiments. Appendix H shows the manual calculations of the single KPI experiments for instance 1. Since the results of Table 5.4 and Appendix H are the same, we prove the correctness of the C2Pa model. We performed the manual calculations for instance 2 in a similar way as the manual calculation for instance 1 as presented in Appendix H. Also, for instance 2 the results are the same proving the correctness of the C2Pa model for different instances.

Scenario	KPI value instance 1	KPI value instance 2
Single utilisation KPI optimization (in %)	55.61	55.94
single cost KPI optimization (in €)	127.00	127.00
single satisfaction KPI optimization	6.40	5.99
single skill match KPI optimization	2.00	-1.33

Table 5.4: Results of the C2Pa model for the single KPI optimization experiments

5.3 Model validation

The goal of the model validation is to evaluate if the results of the model are accurate in comparison with real observations. We validate the model by discussing the outcomes of the model with experts (OTL team). For the validation experiment we have one scenario which is the data instance (Table 5.1) and we use the same 2 instances as the model verification experiment for this scenario. We discuss the following topics: (i) declined projects and (ii) assigned consultants.

5.3.1 Instance 1

Project 0, project 1, project 3, project 4, project 5, project 6, project 7, and project 8 are the declined projects in the first instance. Project 0 is a project that requires 2 consultants. The first consultant for 40 hours per week, and the second 32 hours per week. The project runs from week 31 until 47. When discussing the possible consultants for this project with the OTL, we conclude that only consultant 11 is available for team member role 0 and team member role 1. Since a consultant can only work on one team member role per project and all team member roles need to be filled, declining the project is the only option. Using the C2Pa model results in the same decision. The same applies for project 3, also only consultant 11 is available for both team member roles (2 consultants for both 40 hours per week from week 39 until 47). For the other declined projects, we observe that no consultants are available for assignment: project 1 (2 consultants both 40 hours per week in week 9 until 29), project 3 (2 consultants both 40 hours per week in week 39 until 47), project 4 (2 consultants both 40 hours per week in week 10 until 19), project 5 (1 consultant for 40 hours per week in week 15 until 45), project 6 (1 consultant for 20 hours per week in week 0 until 43), project 7 (2 consultants both 40 hours per week in week 11 until 27), and project 8 (2 consultants both 40 hours per week in week 5 until 34).

When comparing the optimal assignments of the C2Pa model with the assignments of the OTL team for instance 1, the assignments are the same. This is a logical observation since consultant 9 was the only available consultant to be assigned to project 2. Therefore, in case the OTL also sees this assignment option they make the same assignment as the C2Pa model.

5.3.2 Instance 2

Project 0, project 2, project 3, project 6, project 7, and project 8 are the declined projects in the second instance. Project 0 is a project that requires 2 consultants both for 40 hours per week. The project runs from week 10 until 16. When discussing the possible consultants for this project with the OTL, we conclude that only consultant 11 is available for team member role 0 and team member role 1. Since a consultant can only work on one team member role per project and all team member roles need to be filled, declining the project is the only option. We observe that the C2Pa model also noticed this and made the same decision. For the other declined projects, we observe that no consultants are available for assignment: project 2 (1 consultant for 40 hours per week in week 0 until 50), project 3 (1 consultant for 40 hours per week in week 18 until 26), project 6 (2 consultants both 40 hours per week in week 0 until 50), project 7 (1 consultant for 40 hours per week in week 9 until 47), and project 8 (1 consultant for 40 hours per week in week 29 until 45).

When comparing the optimal assignments of the C2Pa model with the assignments of the OTL team for instance 2, the C2Pa model assigns project 4 differently than the OTL. The C2Pa model assigns project 4 to consultant 11, while the OTL team assigns project 4 to consultant 2. When discussing these changes with an OTL and comparing the differences with respect of KPI performance, the OTL agreed that they did not think of this consultant as assignment option. However, the OTL sees the potential of this assignment and agrees that the model assignment is better than their manual assignment.

5.4 Model performance evaluation

This section analyses the model performance by comparing the OTL assignment versus the optimal assignment according to the C2Pa model. Table 5.5 shows the results of this comparison. The C2Pa model increases consultant satisfaction, and decreases the hourly cost for an increase in underqualification. Since the number of declined projects remains the same and the same projects are accepted for both scenarios, the utilisation keeps the same for both scenarios. Moreover, the C2Pa model has a computational time of 0.99 seconds. Note that the differences between the OTL and C2Pa in terms of performance are not that big due to the small instance used for this scenario. Using a larger instance for this experiment was not possible due to the time intensiveness involved with creating such an instance.

KPI	OTL	C2Pa model
Utilisation (in %)	75.40	75.40
Hourly cost (in €)	120.75	115.69
Satisfaction	6.05	6.41
Skill match	-4.80	-5.80
Declined projects	4.00	4.00

Table 5.5: Comparison between performance OTL assignments versus C2Pa model assignments

5.5 Impact of flexibility in start time windows

This section analyses the results of the impact of flexbility in the project start time window sizes. Table 5.6 presents the results of an experiment examining the impact of time window size on the performance of the C2Pa model. The experiment explores various scenarios where the time window size equals 0, 1, 2, 3, or 4 weeks. The key metrics measured include computational time in seconds, declined projects ratio, utilization percentage, average hourly cost in euros, satisfaction, and skill match. The mean and standard deviation values for each metric are provided for different scenarios which are all run 10 times, offering insights into how time window sizes influences the performance of the C2Pa model. We use the same layout for Table 5.7 and Table 5.8.

We expect that increasing the start time window size decreases the number of projects declined due to the created additional flexibility in scheduling and assigning consultants to projects (projects can be scheduled at more time periods leading to more consultants that might be available for executing the project). This increase in flexibility could lead to overcoming the consultant availability constraint resulting in accepting the project. In case this is true, we also make more assignments leading to higher utilizations. However, since the choice of accepting a project only depends if accepting a project would result in a feasible solution, we expect that accepting extra projects comprises the other KPIs (hourly cost KPI, satisfaction KPI, and the skill match KPI).

Table 5.6 confirms the expectation of increased accepted projects, utilisation, hourly cost, and the decrease in skill match. However, the consultant satisfaction KPI is not according to expectation because for a start time window size of 2 and a time window size of 3 the satisfaction increases. The reason why the satisfaction for these two scenarios increase is because not all extra created flexibility (by increasing the time window sizes) could be used for accepting projects. The C2Pa model is then able to use the leftover flexibility for improving the KPIs. In this case the consultant satisfaction.

Exp.	Scenario	Computational time (s)		Dec. projects ratio		Utilisation (in %)		Hourly cost (in €)		Satisfaction		Skill match	
		mean	std dev	mean	std dev	mean	std dev	mean	std dev	mean	std dev	mean	std dev
TW	0 (base)	43.88	0.17	0.70	0.00	55.71	0.17	**128.10**	0.40	5.85	0.02	**-4.11**	0.02
TW	1	41.37	27.03	0.69	0.13	55.71	0.70	129.31	4.76	5.77	0.46	-4.49	4.40
TW	2	40.30	15.82	0.66	0.13	56.07	1.18	128.38	6.64	5.89	0.56	-6.15	4.50
TW	3	44.24	21.71	0.66	0.13	56.07	1.18	128.39	6.64	**5.91**	0.57	-6.10	4.55
TW	4	48.47	29.56	**0.63**	0.16	**56.20**	1.21	128.38	6.24	5.83	0.49	-6.39	5.02

Table 5.6: Effect time window size on the performance of the C2Pa model

5.6 Useability of the C2Pa model with respect to company size

Table 5.7 shows the results for running the company size scenarios. The mean and standard deviation for these scenarios are based on 4 data instances instead of 10, since 6 of the data instances from the 8 consultants and 5 projects scenario led to declining all projects. Instances that declined all projects have an average hourly cost of 0, a satisfaction of 0, and a skill match of 0 and therefore distort the experiment. We therefore decide to remove these data instances to get clear insights. To keep the comparison between the company size scenarios fair, we remove the instances with the same seed value also in the other scenarios.

We expect for the company size experiments that the larger the problem size the more assignment options are available and therefore the better the KPI values will be. Table 5.7 confirms this expectation for the declined projects, utilisation, and satisfaction. However, this does not hold for the hourly cost and the skill match. We do observe an decreasing trend in the skill match from the base case to the larger problem sizes. Nevertheless, the smaller problem size contradicts this trend. The reason why the hourly cost increase is because more assignment options lead to a larger chance of accepting projects. In case the projects could only be accepted when assigning a more expensive consultant, the model will still do this because of BE NL' business rule. The average hourly cost could therefore increase.

Furthermore, we observe an exponential trend between the problem size and the computational times. Increasing the problem size for large companies with the current C2Pa model, therefore becomes problematic (Figure 5.1).

Exp.	Scenario	Computational time (s)		Dec. projects ratio		Utilisation (in %)		Hourly cost (in €)		Satisfaction		Skill match	
		mean	std dev	mean	std dev	mean	std dev	mean	std dev	mean	std dev	mean	std dev
size	8 & 5	8.37	1.41	0.70	0.12	57.24	0.16	131.08	6.15	5.74	0.43	**-1.63**	2.50
size	15 & 9 (base)	66.26	71.96	0.64	0.14	55.86	0.89	**129.63**	3.80	5.62	0.28	-7.41	5.13
size	23 & 14	1492.58	1136.88	0.70	0.09	60.66	0.56	129.74	4.45	5.94	0.38	-6.21	2.84
size	30 & 18	3211.01	2607.22	**0.61**	0.05	**62.62**	0.80	129.96	3.15	**6.01**	0.32	-5.60	3.23

Table 5.7: Effect company size on the performance of the C2Pa model

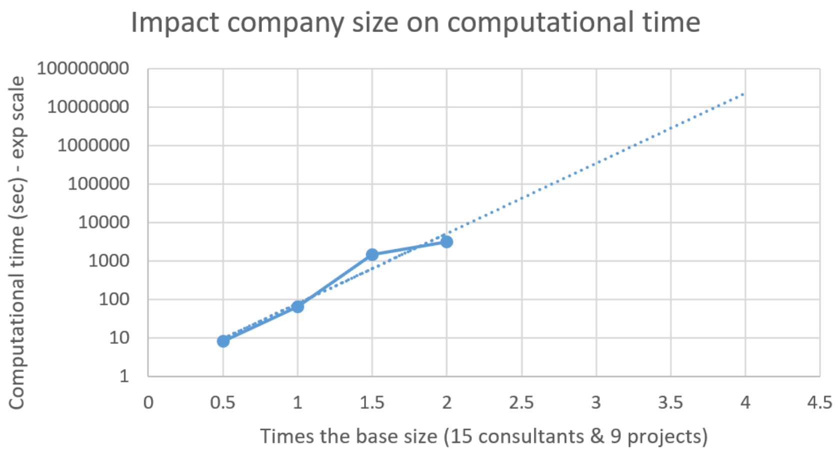

Figure 5.1: Trend computational time with respect to problem size

5.7 Effect organizational capabilities

The experiments involving different consultant skill sets demonstrate how companies with employees of differing skill levels affect the performance. Furthermore, varying the organizational capabilities illustrates how training your employees on skills influences the performance. We expect that increasing the organizational capabilities has no effect on the number of declined projects and the consultant-to-project utilization, since this will not create additional flexibility to overcome the consultant availability constraint. However, we do expect the skill match to increase if the average skill levels increase since more cheaper consultants will have a better fit on the projects, leading to decreasing hourly cost. We do not expect a relationship between increasing the average skill level and the satisfaction. Table 5.8 confirms this expectation. An interesting observation that can be seen from the instances generated for this experiment is that there is a sweet spot for the C2Pa skill match KPI if the average consultant skill level increases between 0.5 and 1 level.

Exp.	Scenario	Computational time (s)		Dec. projects ratio		Utilisation (in %)		Hourly cost (in €)		Satisfaction		Skill match	
		mean	std dev	mean	std dev	mean	std dev	mean	std dev	mean	std dev	mean	std dev
CSL	-0.5	37.08	14.87	0.70	0.14	55.71	0.70	**127.07**	3.83	5.53	0.43	-7.61	4.02
CSL	0	45.16	36.61	0.70	0.14	55.71	0.70	128.10	3.32	5.85	0.46	-4.11	4.62
CSL	0.5	50.53	53.54	0.70	0.14	55.71	0.70	127.67	4.74	5.76	0.66	**-0.67**	1.87
CSL	1	47.73	47.86	0.70	0.14	55.71	0.70	127.75	4.08	**5.89**	0.48	1.63	2.16
CSL	1.5	33.17	4.99	0.70	0.14	55.71	0.70	127.53	4.29	5.51	0.56	3.90	2.73

Table 5.8: Effect organizational capability on the performance of the C2Pa model

5.8 Conclusion

We started this chapter, by establishing a data instance for the experiments. This data instance was based on input data of the D&A service line of BE NL. With this data instance, we verified, validated, and evaluated the performance of the C2Pa model. Table 5.5 proves the effectivess of the C2Pa model compared to the current C2PA procedure. Furthermore, we used this data instance to experiment with the project start time window sizes, company sizes (number of projects and consultants), and the average consultant skill level.

The start time window size experiments prove an increasing relation between the accepted projects, utilisation, and hourly cost. Furthermore, we observed a decreasing realtion with the skill match. We did not observe an relation between the project start time window size and the consultant satisfaction.

The experiments involving the company size suggest an exponential behaviour between the number of projects and consultants and the computational time. The company size experiments also demonstrated the limitation of the C2Pa model for large company sizes. Furthermore, increasing the company sizes proved a positive relation with the number of declined projects, utilisation, and satisfaction.

The experiments involving the consultant skill distribution mostly impacted the C2Pa skill match KPI. However, also the cost where positively influenced when varying the consultant skill distribution. Moreover, we observed that the C2Pa skill match KPI is optimal between an average increase in skill level between 0.5 and 1.

6 CONCLUSIONS AND RECOMMENDATIONS

This chapter gives the conclusions and recommendations following from the research. Section 6.1 concludes this research. Section 6.2 elaborates on the theoretical and practical contribution of this research. Section 6.3 discusses the limitations of the consultant-to-project assignment model. Section 6.4 adresses the recommendations for BE NL resulting from this research. At last, Section 6.5 gives the future research resulting from this research.

6.1 Conclusions

This section concludes this research. The research started with describing the problem. From this problem description, we formulated the main research goal. The main research goal is:

"To develop a Consultant-to-Project Assignment(s) (C2Pa) model that helps improving BE NL' C2Pa procedure by making the C2Pa procedure structured and unambiguous."

The C2Pa procedure is the process of strategically matching consultants with the right expertise, experience, job position, and skill sets to the specific projects while also taking into account their satisfaction working with specific skills. The C2Pa procedure plays an imporant role in the effectiveness and success of client engagements, consultant satisfaction, and the financial performance of the company. The stakeholders for the C2Pa problem are the consultants of BE NL, BE NL itself, and their clients. We solve the main research goal by answering the following research question:

"How can BearingPoint Netherlands create a C2Pa model that helps improving the C2Pa procedure by making the C2Pa procedure structured and unambiguous?"

We use the following sub-research questions to help answering the research question:

1. What is the current situation of C2Pa procedure at BearingPoint Netherlands?
2. What models and approaches related to the C2Pa problem are available in literature?
3. What is a good modelling approach for the C2Pa problem?
4. How does the model perform for different scenarios of the C2Pa problem?

The first sub-research question addresses the current situation at BE NL. The absence of a structured and unambiguous C2Pa procedure hinders the OTL (team) with effectively managing the resource allocation, consultant satisfaction, project quality, and consultant assignment cost, resulting in suboptimal C2Pa that a) fail to balance the needs of all stakeholders involved, b) lack transparancy and visibility, c) are subjective & biased, d) are time intense, and e) lack long-term planning. The reason why BE NL currently has an unstructured and ambiguous C2Pa procedure is threefold. First, there are no clear measurable performance KPIs. Second, the input data is incomplete or absent. Third, the decision-making in the C2Pa problem is complex.

The second sub-research question addresses the models and approaches that are available in literature related to the C2Pa problem. The C2Pa application area deals with methods to match consultants to projects in a way that maximizes the project's success probability while also ensuring client and consultant satisfaction. The C2Pa application area does not have a standard problem base and solution for solving the C2Pa problem. The simultaneous multi-project scheduling and multi-skill staffing problem of Heimerl and Kolisch (2010a) is the most suitable base for modelling the C2Pa problem (Section 3.2). However, the model of Heimerl and Kolisch (2010a) required significant adaptions in constraints and objectives to be able to solve the C2Pa problem. We made the single-objective model of Heimerl and Kolisch (2010a) multi-objective by implementing the revised MCGP of Chang (2008). Next to the hourly cost of assigned consultant KPI which is based on the cost KPI on the model of Heimerl and Kolisch (2010a), we also added the consultant-to-project utilization KPI based on the efficiency of the workforce KPI of Zabihi et al. (2019), consultant satisfaction KPI based on the salesmen satisfaction KPI of Abboud et al. (1998), and the C2Pa skill match KPI on the quality KPI of Chen et al. (2020). Chen et al. (2014) add a parameter to the model of Heimerl and Kolisch (2010a) that specifies the assigned number of employees for task k of project j. We could adapt this parameter to create the project team size constraint.

The third sub-research question addresses the modelling approach for the C2Pa problem. According to the literature review, a MILP model is the most suitable mathematical formulation for creating the C2Pa model. To be able to deal with the multiple objectives of the C2Pa problem, we extend the MILP model by implementing a revised MCGP. This results in the final MILP model that performs multi-project scheduling and assignment of multi-skilled consultants to projects. The MILP model runs in Python and has 5 indices: consultants, projects, time, team members, and skills. The C2Pa model maximizes the consultant-to-project utilization KPI, minimizes the hourly cost of assignments, maximizes the consultant satisfaction KPI, and brings the C2Pa skill match KPI as close to zero as possible. Furthermore, the C2Pa model declines projects in case no suitable assignment is possible.

The fourth sub-research question addresses the C2Pa model's performance for different scenarios. In the benchmark between the OTL assignments and the C2Pa model assignments, we observe that the C2Pa model outperforms the OTL assignments by improving 2 KPIs (decreasing the average hourly cost with 4.19% and increasing the satisfaction with 5.95%) and keeping one KPI the same (utilisation since the same projects are assigned). The C2Pa model compromises on the C2Pa skill match KPI by making the assignments slightly more underqualified (-1). Moreover, the C2Pa model's computation time is 0.99 seconds. Notice that due to the time intensiveness of creating the benchmark instance we were only able to perform the benchmark on a small instance (creating the assignments for the OTL scenario costs a lot of time for the OTL team).

For the experiments with the flexible project start time windows, we expected that increasing the time window sizes decreases the number of declined projects. Furthermore, we expect the consultant to project utilization to increase, while the other KPIs are compromised. The experiments proved the expectation of increased accepted projects, utilisation, hourly cost, and the decrease in skill match. However, the consultant satisfaction KPI is not according to expectation due to an increase in satisfaction for a start time window size of 2 and 3 weeks.

For the experiments that test the useability of the C2Pa model with respect to the company size, we expect that increasing the company size improves the KPI values. The experimental results proved that this is the case for the number of declined projects, utilisation, and cost. However, this does not hold for the hourly cost and the skill match. Furthermore, we observed an exponential trend between the company (problem) size and the computational times. For large company, the C2Pa model in current form therefore becomes problematic.

For the experiments with the different organizational capabilities, we expect that increasing the organizational capabilities has no effect on the number of declined projects, and the utilisation. However, we do expect the skill match to increase and the cost the decrease. Furthermore, we do not expect a relationship between the organizational capabilities and the satisfaction. The experimental results proved the expectations. Moreover, based on these instances even a sweet spot for the C2Pa skill match KPI (sweet spot when skill match KPI equals 0) was found. The sweet spot is reached between an average consultant skill level increase between 0.5 and 1.

Now that we answered all sub-research questions, we are able to address the main research question. By implementing the C2Pa model, BE NL creates a structured and unambiguous C2Pa procedure that improves the C2Pa with respect to balancing the different stakeholders' needs and solves the current C2Pa procedure issues. Section 6.4 elaborates more in detail about the implementation of the C2Pa model and recommendations for BE NL. Subsection 6.2.2 describes the advantages of implementing the C2Pa model for BE NL more in detail.

6.2 Contribution

This section describes the theoretical and practical contribution of the research.

6.2.1 Theoretical contribution

As stated in Section 3.2, there is no standard problem and solution for the C2Pa application area. The theoretical contribution of this research lies in the formulation of a foundational framework (outlining the core elements, relationships, and underlying principles that define and characterize the problem) that describes the problem of assigning and scheduling multi-skilled consultants to multiple projects, and provides a modelling approach to solve this problem. The C2Pa model uses the simultaneous multi-project scheduling and multi-skill staffing problem of Heimerl and Kolisch (2010a) as base. However, the C2Pa required significant adaptions in constraints and objectives. We made the single-objective model of Heimerl and Kolisch (2010a) multi-objective by implementing the revised MCGP extension of Chang (2008). Next to the hourly cost of assigned consultant KPI which is based on the cost KPI on the model of Heimerl and Kolisch (2010a), we also added the consultant-to-project utilization KPI based on the efficiency of the workforce KPI of Zabihi et al. (2019), consultant satisfaction KPI based on the salesmen satisfaction KPI of Abboud et al. (1998), and the C2Pa skill match KPI on the quality KPI of Chen et al. (2020). Moreover, we implemented the project priority element based on Afruzi et al. (2020), and the project team size element based on Chen et al. (2014). Furthermore, this research provides insights in the useability of the C2Pa model for different company sizes, the impact of different organizational capabilities on the results of the C2Pa model, and the impact of different start time window sizes on the results of the C2Pa model.

6.2.2 Practical contribution

This research has multiple practical contributions to BE NL. First of all, the C2Pa model solves the unstructured and ambiguous C2Pa procedure at BE NL by clearly defining and assessing the KPIs, and by simplifying the complex decision-making of the C2Pa problem. Second, the C2Pa model assists the OTL (team) with effectively managing the resource allocation, consultant satisfaction, project quality, and consultant assignment cost resulting in balanced stakeholders, transparancy and visibility in decision-making, objective assignments, long-term planning, and faster and better decisions. In the benchmark between the OTL assignments and the C2Pa model assignments, we observe that the C2Pa model outperforms the OTL assignments by improving 2 KPIs (decreasing the average hourly cost with 4.19% and increasing the satisfaction with 5.95%) and keeping one KPI the same (utilisation since the same projects are assigned). The C2Pa model compromises on the C2Pa skill match KPI by making the assignments slightly more underqualified (-1). Moreover, the C2Pa model's computation time is 0.99 seconds. Notice that due to the time intensiveness of creating the benchmark instance we were only able to perform the benchmark on a small instance (creating the assignments for the OTL scenario costs a lot of time for the OTL team).

6.3 Limitations

Next to the benefits of the C2Pa model, also some limitations exist. We identify the following limitations:

6.3.1 Input data

The quality of the outcome of the C2Pa model is dependent on the input of the C2Pa model. The input relies on the data quality and data availability.

One significant limitation concerning the quality of the input data is that the C2Pa model relies on subjective input from consultants regarding their skill satisfaction and skill levels. While these insights are crucial for matching consultants to projects that align with their interests and strengths, the subjectivity of these self-reflections introduces potential inaccuracies and a degree of variability (for example in case of underestimating or overestimating the skill levels). Ensuring reliable and consistent reporting of the satisfaction and skill levels is an ongoing challenge.

One significant limitation concerning the availability of the input data is that the C2Pa model needs up-to-date and comprehensive input data. In cases where the input is outdated or incomplete, the model's utility and accuracy may be compromised.

6.3.2 Computational time

The potential exponential behaviour of the computational times are a significant limitation for the useability of the C2Pa model. The computational time of 1.5 times the size of the D&A team already took approximately 60 hour, making the C2Pa model in its current form impractical for application in larger companies.

6.3.3 Dashboard

The development of the C2Pa dashboard was outside the scope of this research, and therefore only developed up to the minimum viable product (MVP) stage. This stage shows the outcomes of the C2Pa model and eases the comparison between experiments and input settings. However, much more value can be created by the dashboard when the dashboard is developed further. Especially with respect to the Gantt chart, that currently is not able to visualize the assignment of multiple projects to the same consultant at the same time.

6.4 Recommendations

Based on the research, we set up the following recommendations for BE NL:

6.4.1 C2Pa model implementation and integration

The issue with BE NL' current C2Pa procedure is that this procedure leads to suboptimal C2Pa that a) fail to balance the needs of all stakeholders involved, b) lack transparancy and visibility, c) are subjective & biased, d) are time intense, and e) lack long-term planning. Since the C2Pa model is proven to be succesful in solving these issues, we recommend BE NL to implement the C2Pa model in the C2Pa procedure as a decision-support tool.

Integrating a model in the current C2Pa procedure can be hard, so we therefore also make some recommendations concerning the model integration. We identified two important aspects to enlarge succesfull model integration. The first aspect is keeping the consultants' availability, satisfaction, and skill levels up to date. This can be done by creating guidelines. For example, update the consultants' availability, satisfaction, and skill level for each team member of the project after each project close. The second aspect is making sure that the OTL (team) starts using the C2Pa model in their C2Pa procedure. This can be done by giving a workshop to the OTL explaining the purpose and benefits of the model as well as giving instructions how the C2Pa model works. Giving this workshop together with providing a instruction manual will enlarge the changes that the OTL (team) will start using the tool.

6.4.2 Data warehouse

Since BE NL currently does not have a data warehouse for storing all information required for the C2Pa procedure centrally, all the data needs to be manually loaded into the tool. This costs time and is prone to errors. Implementing a data warehouse would make this step redundant and enables the C2Pa model to draw its information directly from the data warehouse. Another benefit of using a data warehouse is that the data is always up-to-date since it is directly connected to the source generating the information.

6.4.3 Interactive improvement

Another recommendation for BE NL is to transform the model into an application that manages the input, the C2Pa model itself, and the output (dashboard). This application will streamline data input, processing and output, leading to higher efficiency and less risk of errors. The data of the application could possibly be stored into a data warehouse to leverage these benefits as well.

Further developing the dashboard to enable more advanced analytics of the results and a better user experience should also be part of the interactive improvement. Currently, the dashboard could only be created as a minimum viable product (MVP) due to not being in the scope of this research but much more value can be created when the dashboard is developed further.

6.4.4 Improving the availability of input data

The model needs detailed project information like required project skill levels. Since transforming the project description into required project skill levels can be quite time consuming we recommend to create a prompt for generative AI like Bing Copilot or ChatGPT to automatically substract the required skill levels from the project description. In this way the user could copy and paste the project description in the generative AI and receives the skill levels for the required project skills as output. However, make sure to use a generative AI that is in line with the company's policy and the GDPR.

6.4.5 Reduce computational times

Subsection 6.3.2 already mentioned the limitations of larger problem instances for C2Pa model. A possible solution for larger problem instances is implementing a metaheuristc. During the literature research, we observed that SA outperformed the other metaheuristics in both computational time and performance (Haghi et al., 2017). We therefore recommend BE NL to implement simulated annealing. Section 6.5.1 provides more information about how to do this.

6.4.6 C2Pa model input extension

Currently the C2Pa model only focuses on the D&A service line. However, since the issues of the current C2Pa procedure are experienced in every service line it is recommended to extend the model to all service lines. In this way, the C2Pa model can do the assignments for BE NL as a whole. Extending the C2Pa model for all service lines can easily be done and does not require changes in the model itself. Defining the skills for each service line in a similar way as Appendix B in combination with extending the input files is sufficient. The input files should include the projects of the other service lines including project characteristics and the consultants of the other service lines including the consultant characteristics.

6.5 Future research

The beforementioned limitations create opportunities for potential future research. We list the most promising future research below:

6.5.1 Simulated Annealing

To improve useability of the C2Pa model for large problem instances and improve testing and experimenting with the C2Pa model, lowering the computational times is desired. We already performed research on how to implement simulated annealing for the C2Pa problem. Appendix J shows this research. Due to the potential decrease in computational times makes finishing the implementation of simulated annealing (best performing metaheuristic for the C2Pa problem (Haghi et al., 2017)) for the C2Pa problem very valuable and highly recommended. However, take into account that optimising the C2Pa problem with simulated annealing is different than optimising the C2Pa problem exact. The performance in terms of assignment solution and computational time should therefore be analysed.

6.5.2 Extending the C2Pa model

During this research, we gathered many insights in the C2Pa model. However due to the scope we had to leave some potentially beneficial aspects out of the C2Pa model. Therefore, we discuss these aspects in this subsection. Market opportunities and growth potential as well as sustainability and environmental friendless are project characteristics that are currently not taken into account during the C2Pa problem. Including these aspects in the model and investigate their impact would be a good future research aspect. The most convenient way of adding these aspects would be in the priority factor.

Moreover, the C2Pa model currently does not include personal characteristics when deciding on the C2Pa. Adding this to the C2Pa model could be beneficial since clients could desire a consultant based on personal traits like for example independent worker, critical, analytical, goalgetter, social, connecting, and so on. Adding this to the C2Pa should therefore be considered. However, keep in mind that the current complexity of the model is already quite high and adding such an aspect would only increase this complexity level even more.

6.5.3 Developing a standard method for defining the relevant project skills

To enable the C2Pa model to also be useful for other companies than BE NL, we should develop a method that companies can use to identify the relevant project skills they encounter during their projects. Identifying these skills is an essential step for using the C2Pa model since these skills are the basis for the C2Pa model. Future research in exploring frameworks to identify the required project skills that are company independent is therefore valuable.

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A LIST OF USED TOOLS

During the preparation of this work, I used:

- TeXstudio and MiKTeX Console to create this report
- Mendeley to manage the citations
- ChatGPT to discuss certain topics and for ideation
- Miro to draw some of the images
- Lucidchart to draw some of the images
- Excel for the dashboard
- Python for running the C2Pa model and creating the results

After using these tools/services, I thoroughly reviewed and edited the content as needed, taking full responsibility for the final outcome.

B SKILLS AND COMPETENCES OF D&A PROJECTS

By combining the different capability models of the different data domains (data management, data analytics and data engineering), BE NL created a comprehensive capability model. In addition to the capabilities present in the different models, BE NL added additional capabilities they saw in their daily practice as consultants or are seen as important trends by market research firms. Figure B.1 shows the resulting capability model BE NL wants to consider during the C2Pa process. Figures B.2 and B.3 explain the definitions of the capabilities. Furthermore, Table B.1 and B.2 explain the scales for the satisfaction and skill levels for the capabilities respectively.

Figure B.1: Overview of D&A capabilities (BearingPoint Netherlands, 2023a)

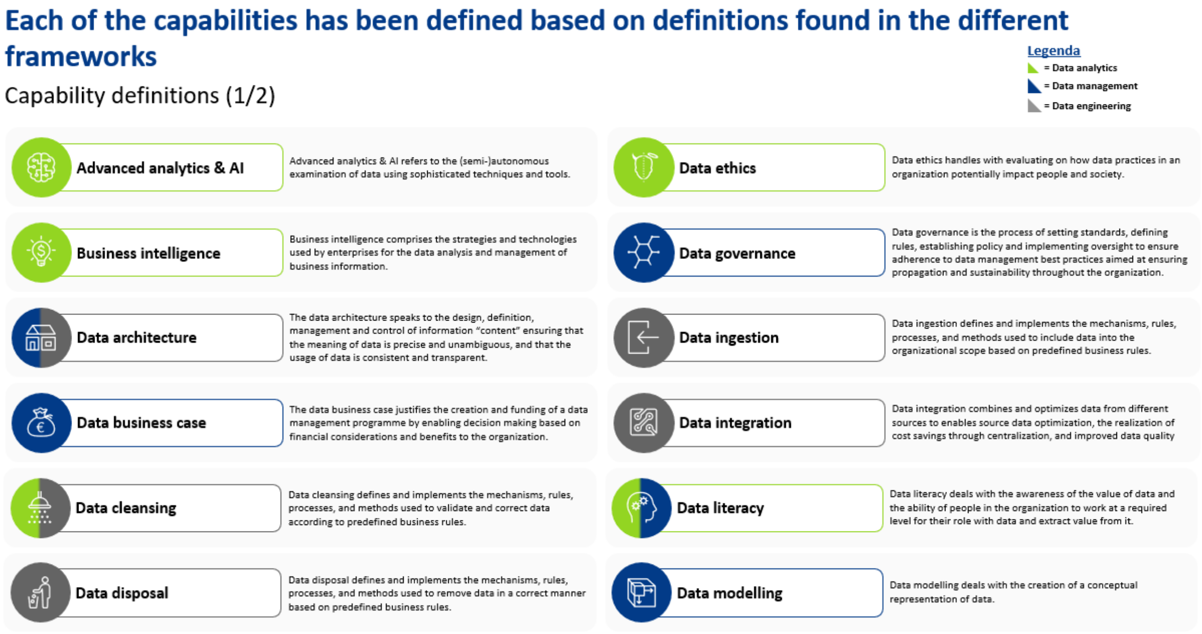

Figure B.2: D&A capability definitions 1/2 (BearingPoint Netherlands, 2023a)

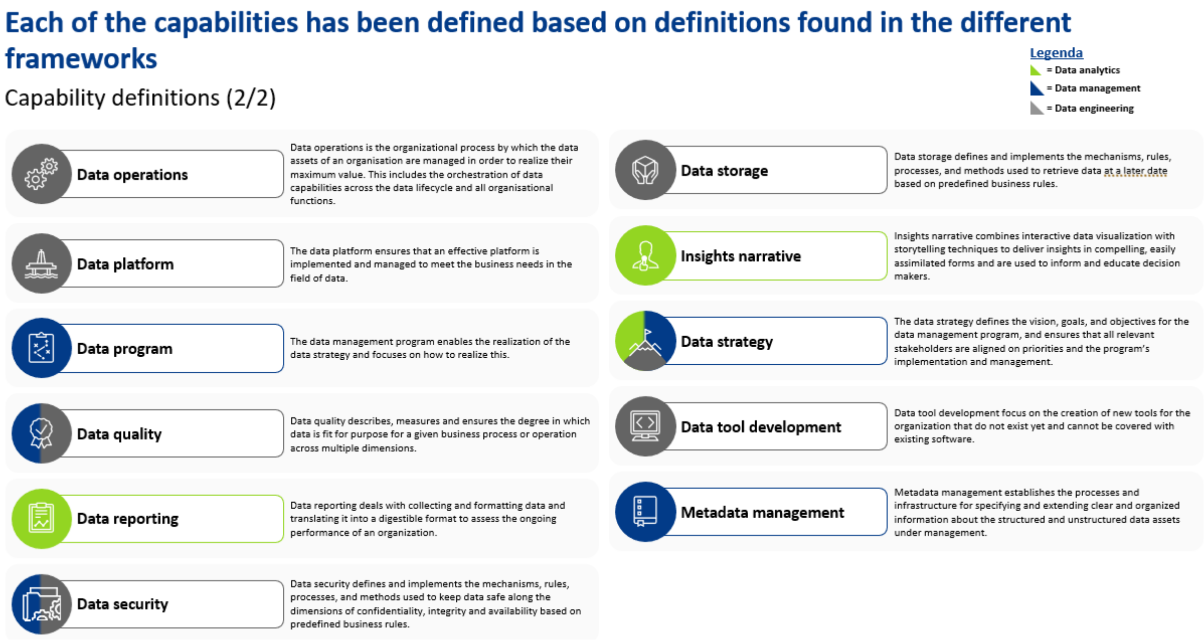

Figure B.3: D&A capability definitions 2/2 (BearingPoint Netherlands, 2023a)

Skill level	Explanation
0	No experience
1	Basic experience - knowing the basic features and possibilities
2	Professional experience - basic experience + implementation experience
3	Expert experience - knowing all ins and outs + many implementation experience

Table B.1: Skill level of the certain skill or competence

Satisfaction scale	Explanation with respect to assignment to skill/ competence
1	Extremely dissatisfied
2	Very dissatisfied
3	Dissatisfied
4	Somewhat dissatisfied
5	Neutral to the negative side
6	Neutral to the positive side
7	Somewhat satisfied
8	Satisfied
9	Very satisfied
10	Extremely satisfied

Table B.2: Satisfaction scale with respect to the satisfaction of the consultant in working on or developing in a certain skill or competence

C RESOURCE AND BEACH REQUEST TEMPLATES

This appendix shows the template BE NL currently uses for requesting resource and beach requests.

Resource Request	
Requirement: CRM stage 6+ & probability >60%	
Response needed	
Deadline response When does the client need to know	
Client name	
Project title	
Project description	
Start date	
End date	
Utilization %	
Level MA,C,SC,M,D,P	
Competencies / skills	
Preferred resource Name(s) of colleague	
EM responsible	
Extra information (if applicable)	

Beach Request	
Activity title	
Activity description	
Impacted segment (AIM,BCM,CGR,CLR,CME,GPS,INS,UPT)	
Impacted service line (P&S,C&G,D&A,TEC)	
Requested hours	
Start date	
End date / Deadline Remove which one's not applicable	
Level	
Preferred resource Name(s) of colleague	
Number of clients	
Expected conversion %	
Extra information (if applicable)	

Figure C.1: Resource and Beach request templates (BearingPoint Netherlands, 2023b)

D OVERVIEW NOTATIONS MATHEMATICAL MODEL

This appendix shows the notations (in alphabetic order) that are used in the mathematatical model.

Notation	Description
ap_p	Binary decision variable that equals 1 in case project p is accepted (all team member slots are assigned to consultants), and 0 otherwise.
α^+_{cost} and α^-_{cost}	Positive and negative weight attached to the normalized sum of deviations of e^+_{cost} and e^-_{cost}
α^+_{util} and α^-_{util}	Positive and negative weight attached to the normalized sum of deviations of e^+_{util} and e^-_{util}
α^+_{satis} and α^-_{satis}	Positive and negative weight attached to the normalized sum of deviations of e^+_{satis} and e^-_{satis}
c_i	Hourly cost parameter for assigning consulant i to a project based on the consultant's job position (see Table 2.1)
$CH_{t,p,s}$	Chargeable hours parameter for required skill s of project p at period t
$csl_{s,i}$	Consultant i's skill level parameter for skill s (according to the skill level range as specified in Table B.1)
$css_{s,i}$	Consultant i's skill satisfaction parameter for skill s (according to the satisfaction scale as specified in Table B.2)
d^+_{cost} and d^-_{cost}	Positive and negative deviation variable between the hourly cost of assigned consultants KPI and the continuous variable that represents a value in the aspiration level interval range
$d^+_{i,util}$ and $d^-_{i,util}$	Positive and negative deviation variable between the consultant-to-project utilization rates KPI and the continuous variable that represents a value in the aspiration level interval range for consultant i
$d^+_{i,p,match}$ and $d^-_{i,p,match}$	Positive and negative deviation variable between the C2Pa skill match KPI and the continuous variable that represents a value in the aspiration level interval range for consultant i and project p
d^+_{satis} and d^-_{satis}	Positive and negative deviation variable between the consultant satisfaction rates KPI and the continuous variable that represents a value in the aspiration level interval range
e^+_{cost} and e^-_{cost}	Positive and negative deviation variable between the continuous variable that represents a value in the aspiration level interval range and the desired minimum or maximum aspiration level of the hourly cost of assigned consultants KPI
$e^+_{i,util}$ and $e^-_{i,util}$	Positive and negative deviation variable between the continuous variable that represents a value in the aspiration level interval range and the desired minimum or maximum aspiration level of the consultant-to-project utilization rates KPI for consultant i

Notation	Description
e^+_{satis} and e^-_{satis}	Positive and negative deviation variable between the continuous variable that represents a value in the aspiration level interval range and the desired minimum or maximum aspiration level of the consultant satisfaction rates KPI
$em_{i,p}$	Binary parameter that equals 1 in case consultant i is working as EM on project p and 0 otherwise
emh	Parameter that represents the hours an EM needs per project per week for performing the EM tasks
ES_p	Project p's earliest start time parameter
i	Consultant index i with $i = 1, ..., I$
I	Number of consultants parameter
LF_p	Project p's latest finish time where $LF_p = LS_p + d_p - 1$
LS_p	Project p's latest start time parameter
m	Team member index m with $m = 1, ..., m_p$
m_p	Number of team members in project p parameter
$NCH_{t,p,s}$	Non-chargeable hours parameter for required skill s of project p at period t
$NH_{i,t}$	Net hours parameter of consultant i in period t
p	Project index p with $p = 1, ..., P$
P	Number of projects parameter
$pd_{p,t}$	Binary auxiliary variable that equals 1 in case project p is in execution at time t and 0 otherwise
$PH_{p,m}$	Number of project hours for team member m of project p for every t during the project. $PH_{p,m}$ remains constant during the project (does not change).
$psl_{s,p}$	Project p's skill requirement level parameter for skill s (according to the skill levels range as specified in Table B.1)
pt_p	Project p's processing time parameter
pv_p	Priority value parameter for project p according to (Subsection 2.4.3)
$q_{p,s,i}$	Binary parameter underqualification for skill s for consultant i on project p. $q_{p,s,i}$ = $\begin{cases} 1\, if\, psl_{s,p} \geq csl_{s,i} \\ 0\, otherwise \end{cases}$
$rs_{p,s}$	Binary parameter if skill s is required for project p. $rs_{p,s}$ = $\begin{cases} 1\, if\, psl_{s,p} \geq 1 \\ 0\, otherwise \end{cases}$
s	Skill index s with $s = 1, ..., S$
S	Number of skills parameter
$st_{p,m}$	Number of required skills of project p that are assigned to team member m parameter.
t	Time index t with $t = 1, ..., T$
T	Number of time in planning horizon parameter
$TotMaxAbsCost$	The total maximum absolute hourly cost is a parameter that represents the maximum absolute value of the hourly cost of assigned consultants KPI. The maximum absolute cost value is 165.

Notation	Description
$TotMaxAbsMatch$	The total maximum absolute skill match is a parameter that represents the maximum absolute value of the C2Pa skill match KPI. The maximum absolute C2Pa skill match value is reached when a project requires a skill at expert level (3) while the consultant does not have this skill (0). The skill match for the required project skill would then become $0^2 - 3^2 = 9$. Since in the absolute worst case this could be required for all project skills and all projects we multiply this value by the number of projects P and the number of skills S. Therefore $TotMaxAbsMatch = (\max(PSL_{s,p}))^2 \cdot P \cdot S$.
$TotMaxAbsSatis$	The total maximum absolute satisfaction is a parameter that represents the maximum absolute value of the consultant satisfaction KPI. The maximum satisfaction that a consultant can give a certain skill is 10. Therefore $TotMaxAbsSatis = 10$.
$TotMaxAbsUtil$	The total maximum absolute consultant-to-project utilization is a parameter that represents the maximum absolute value of the consultant-to-project utilization KPI. The maximum utilization that a consultant can achieve is 100 percent. Therefore $TotMaxAbsSatis = 100$.
TPT	Auxiliary variable that represents the total project hours for all accepted projects in the planning horizon.
TS	Auxiliary variable that represents the number of required skills parameter for all accepted projects in the planning horizon.
TPT_{max}	Parameter that represents the total project hours for all projects in the planning horizon.
TS_{max}	Sum of the number of required skills parameter for all projects in the planning horizon.
$u_{p,t}$	Binary decision variable that equals 1 if project p starts at time t and 0 otherwise.
$w_{p,s,i}$	Binary parameter overqualification for skill s for consultant i on project p. $w_{p,s,i}$ = $\begin{cases} 1\, if\ csl_{s,i} \geq psl_{s,p} \\ 0\, otherwise \end{cases}$
$w_{decline}$	Weight attached to the normalized penalty factor for declining a project
w^+_{cost} and w^-_{cost}	Positive and negative weight attached to normalized deviations of the hourly cost of assigned consultants goal (d^+_{cost} and d^-_{cost})
w^+_{util} and w^-_{util}	Positive and negative weight attached to normalized deviations of the total consultant-to-project utilization rates goal (d^+_{util} and d^-_{util})
w^+_{satis} and w^-_{satis}	Positive and negative weight attached to normalized deviations of the consultant satisfaction rates goal (d^+_{satis} and d^-_{satis})
w^+_{match} and w^-_{match}	Positive and negative weight attached to normalzied deviations of the C2Pa skill match goal (d^+_{match} and d^-_{match})
$WH_{i,t}$	Parameter that represents the working hours of consultant i at time t
$v_{i,p,m,s}$	Binary auxiliary variable that equals 1 in case consultant i is assigned to team member role m and skill s of project p and 0 otherwise
$x_{i,p,t,m,s}$	Binary decision variable that equals 1 in case consultant i is assigned to team member slot m and skill s of project p at time t, and 0 otherwise.
y_{cost}	Continuous variable that represents a value in the aspiration level interval range of the hourly cost of assigned consultants KPI

Notation	Description
$y_{i,util}$	Continuous variable that represents a value in the aspiration level interval range of the consultant-to-project utilization rates KPI for consultant i
y_{satis}	Continuous variable that represents a value in the aspiration level interval range of the consultant satisfaction rates KPI
$z_{i,p,m}$	Binary auxiliary variable that equals 1 in case consultant i is working as team member m on project p

E NORMALIZATION OF OBJECTIVES

In literature, multiple normalization methods for objectives exist. In this appendix we explain the most common ones: min-max normalization, z-score normalization(standardization), decimal scaling, vector normalization(unit vector), sum normalization(equally weighted objectives), and Chebyshev normalization.

E.1 Min-max normalization

The min-max normalization is suitable when objectives have similar ranges and shapes. Min-max utilization is sensitive to outliers. Min-max normalization may not be the best choice for our model since the KPIs have significant variations in the ranges of the KPIs (satisfaction between 1 and 10, while cost between 0 and 100, and cost between 0 and 1000/1000000).

$$\text{Min-Max Normalization:} \quad X_{\text{normalized}} = \frac{X - \text{min}(X)}{\text{max}(X) - \text{min}(X)}$$

E.2 Z-score normalization(standardization)

The z-score normalization is suitable when objectives have different scales and approximately follow a Gaussian (normal) distribution. The z-score normalisation is less sensitive to outliers than min-max scaling, however z-score normalisation requires the standard deviation and mean of the deviation for each KPI. Since we do not have the time for each experiment to run multiple times to calculate the mean and standard deviation this is not a suitable method.

$$\text{Z-Score Normalization:} \quad Z = \frac{X - \mu}{\sigma}$$

E.3 Decimal scaling

The decimal scaling is suitable when objectives have a wide range of values (wide scale/magnitude). Decimal scaling simplifies the computations, but may not be suitable for objectives with large variations (large spread in scale). Our problem can have large deviations in for example the cost KPI, making this method less usable.

$$\text{Decimal Scaling:} \quad X_{\text{normalized}} = \frac{X}{10^d}$$

E.4 Vector normalization(unit vector)

The vector normalization is suitable when the direction of the vector is more important than its magnitude. This method is not suitable since the magnitude of the deviations matter in the C2Pa problem.

$$\text{Vector Normalization:} \quad X_{\text{normalized}} = \frac{X}{\|X\|}$$

E.5 Sum normalization(equally weighted objectives)

The sum normalization is suitable when all objectives are considered equally important. Sum normalization is often used when dealing with percentages or proportions. However, the C2Pa problem has varying ranges and magnitudes in the deviations to the KPIs making the sum normalization method less suitable.

$$\text{Sum Normalization:} \quad X_{\text{normalized}} = \frac{X}{\sum_i X_i}$$

E.6 Chebyshev normalization

The Chebyshev normalization is suitable when the largest absolute value across objectives is critical. Chebyshev normalization is appropriate when extreme values should have a significant impact on the overall analysis (they become the largest value) and when you might be dealing with outliers. Chebyshev normalization involves dividing each element by the largest absolute value, ensuring that the range of normalized values is [-1,1]. This normalization method might be a reasonable choice for the C2Pa problem, giving the varying ranges and magnitudes of deviations to the KPIs in the C2Pa problem.

$$\text{Chebyshev Normalization:} \quad X_{\text{normalized}} = \frac{X}{\text{max}(|X|)}$$

F INPUT DATA D&A SERVICE LINE C2PA MODEL BASE CASE

This appendix explains the input data for the base case. We use the data of the D&A service line as input. Section 2.5 explained how we gathered the data and the reason why we only chose the D&A service line. The input for the C2Pa model consists of several categories with the following names: parameters, consultants, projects, skills, time horizon, consultant availability, consultant skill levels, consultant satisfaction levels, project hours per team member, and project skill level. This chapter only gives the input values for the C2Pa model, but recall that Chapter 4 provided explanations why each input is necessary for the C2Pa model.

F.1 Parameters

The parameters input consists of the weights, normalization factors for the KPIs and the parameter that defines the EM hours per project per week. Table F.1 specifies these input values. Furthermore, the weight for declining a project is set to a large number to make sure that projects are only declined when they cannot be executed (BE NL's policy).

Parameter	Value
w^{+}_{cost}	1
w^{-}_{cost}	1
w^{+}_{util}	1
w^{-}_{util}	1
w^{+}_{match}	1
w^{-}_{match}	1
w^{+}_{satis}	1
w^{-}_{satis}	1
$w_{decline}$	200,000,000

Parameter	Value
α^{+}_{cost}	1
α^{-}_{cost}	1
α^{+}_{util}	1
α^{-}_{util}	1
α^{+}_{satis}	1
α^{-}_{satis}	1

Parameter	Value
$TotMaxAbsCost$	max$(c_i) \cdot 40 \cdot$ sum(pt_p)
$TotMaxAbsUtil$	100
$TotMaxAbsMatch$	(max$(PSL_{s,p}))^2 \cdot P \cdot S$
$TotMaxAbsSatis$	10

Parameter	Value
emh	4

Table F.1: Input base case parameters C2Pa model

F.2 Consultants

The consultants input consists of information about the consultants like job position and consultant number. The D&A team of BE NL currently consists of 15 consultants.

F.3 Projects

The projects input consists of project number, earliest start week, latest start week, number of team members, project duration (in weeks), priority value, binary value representing if the project is a beach request or not, the EM (consultant number), and the project name. Table F.2 visualizes these inputs. Note that the EM column is left empty, because the EMs of the projects are not in the consultant set which means that they can be left out. Furthermore, the project names are left out due to confidentiality. Together with experts from BE NL we decide to analyse 9 projects and use them as input for the C2Pa model.

project	earliest start (wk)	latest start (wk)	team members	project duration	priority value	beach request (binary)	EM (consultant nr)
0	32	32	1	17	1	0	
1	25	25	1	10	1	0	
2	32	32	1	3	1	0	
3	27	31	1	21	1	0	
4	25	30	1	2	1	1	
5	30	34	1	1	1	1	
6	11	11	2	1	1	1	
7	12	12	2	6	1	0	
8	17	21	1	13	1	0	

Table F.2: Input base case projects C2Pa model

F.4 Skills

The skills input consists of skill number, skill name, and skill description. Appendix B gives the skill names with their definitions used for applying the C2Pa model. The D&A team of BE NL identifies 23 skills.

F.5 Time horizon

The time horizon input defines the planning horizon of the C2Pa model in weeks. In BE NL case 52 weeks.

F.6 Consultant availability

The consultant availability input gives the time limitation the tool has to deal with when deciding on the assignment and scheduling of consultants to projects. For the C2Pa tool we use two instances for the consultant availability: one for verifying the model, and one that represents the current situation of BE NL.

The full consultant availability instance for verifying the model assumes that every consultant (i) has full availability during the entire planning horizon ($\forall t$) and works for 40 hours per week ($NH_{i,t} = 40$). The full availability scenario simplifies the calculations and makes the model validation (Section 5.3) and model verification (Section 5.2) easier, since we know that the consultant availability will always start with 40 hours per consultant per time period.

The realistic consultant availability instance represents the current situation of BE NL and takes care of the consultant's actual work hours per week, projects currently working on (until completion), projects in the future in case the consultant is already assigned to this project, and employement start date. Table F.3 shows an example of how this looks like.

Consultant \ Time	0	1	2	3	4	...	51
0	24	24	0	0	0		8
1	0	8	8	8	27.2		32
2	0	0	0	0	0		0
3	12	12	12	12	12		0
4	0	0	0	0	0		0
5	0	0	0	0	0		40
6	0	3.2	4	4	4		0
7	40	0	0	0	0		40
8	0	0	0	0	0		40
9	0	0	0	0	0		3.6
10	0	0	0	0	0		8
11	0	0	0	0	0		40
12	40	40	0	0	0		40
13	0	0	0	0	0		6.4
14	0	0	0	0	0		40

Table F.3: Input base case consultant availability realistic instance C2Pa model. The table should be read in the following way: Consultant 0 has 24 hours available at week 0 (time).

F.7 Consultant skill levels and consultant satisfaction levels

The consultant skill level input gives the skill level of the consultants with respect to the skills. The consultant satisfaction level input gives the satisfaction of the consultants with respect to the skills. Appendix B specifies the scales for both levels. Table F.4 shows the skill level input (left) and satisfaction input (right) for each consultant for the C2Pa model.

Skill \ Consultant	0	1	2	3	...	14
0	0	1	0	3		2
1	1	2	1	3		2
2	1	1	0	1		2
3	2	0	0	2		0
4	1	2	0	2		1
5	1	0	0	0		0
6	2	0	1	0		2
7	3	1	3	0		1
8	1	3	0	1		1
9	1	2	0	0		2
10	3	0	1	1		1
11	2	1	1	1		2
12	0	1	0	0		1
13	0	0	1	0		2
14	3	0	3	0		2
15	2	1	2	1		1
16	1	2	1	3		1
17	2	0	2	0		1
18	2	3	0	1		2
19	3	1	2	1		1
20	0	3	0	0		0
21	1	1	1	2		1
22	1	1	0	0		1

Skill \ Consultant	0	1	2	3	...	14
0	1	7	6	8		6
1	1	8	7	7		7
2	7	7	5	3		7
3	8	4	8	10		3
4	6	6	4	1		6
5	6	5	4	5		5
6	8	1	8	7		8
7	10	3	10	1		7
8	4	10	4	1		4
9	4	9	4	1		6
10	9	3	8	8		7
11	7	8	6	6		8
12	1	7	4	1		3
13	1	6	4	1		3
14	9	4	9	1		4
15	6	4	8	4		7
16	7	8	8	7		7
17	7	4	7	1		2
18	5	9	4	1		7
19	10	3	10	6		6
20	1	10	4	1		7
21	6	7	8	8		8
22	7	5	6	1		8

Table F.4: Input base case consultant's skill levels (left) and satisfaction (right) C2Pa model. From the left table it can be seen that consultant 0 has a skill level of 0 (no experience) for skill 0. From the right table it can be seen that consultant 0 has a satisfaction of 1 (extremely dissatisfied) for developing or working with skill 0.

F.8 Project hours per team member

The project hours per team member input shows the number of hours per week a team member is required to spend on project execution. Table F.5 shows the input for the C2Pa model.

Project \ Team member	0	1
0	40	0
1	40	0
2	20	0
3	32	0
4	16	0
5	4	0
6	20	20
7	40	40
8	16	0

Table F.5: Input base case project hours per team member C2Pa model.

F.9 Project skill level

The project skill level input gives the required skill levels for the project. Appendix B specifies the scale for the required skill levels. Table F.6 shows the required project skill levels for the C2Pa model.

Skill \Project	0	1	2	3	4	5	6	7	8
0	0	1	2	0	2	0	2	2	0
1	0	2	2	3	0	0	1	1	0
2	1	0	0	2	0	0	0	0	0
3	0	1	0	0	0	0	1	1	0
4	0	0	1	2	0	0	0	0	0
5	0	1	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	1
8	0	1	0	0	0	0	2	2	0
9	0	1	0	2	0	0	2	2	0
10	0	0	0	0	0	0	0	0	0
11	2	1	0	3	2	1	1	1	0
12	1	1	0	2	0	0	1	1	0
13	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	1
15	0	1	1	3	0	0	3	3	0
16	0	2	2	3	1	2	2	2	0
17	0	0	0	0	0	0	0	0	1
18	0	1	0	0	0	0	0	0	0
19	0	1	0	2	0	1	2	2	0
20	0	0	0	0	0	0	0	0	2
21	0	0	0	2	0	2	0	0	0
22	0	0	0	0	0	0	0	0	0

Table F.6: Input base case project skill levels C2Pa model.

G INPUT DATA C2PA MODEL EXPERIMENTAL CASE

This appendix shows the datasets of consultant availability, project duration, and project hours per time period per team member for all service lines of BE NL in 2022-2023.

PH value	40	36	32	28	24	20	16	12	10	8	4	2
Occurance	88	4	13	2	12	8	7	1	1	1	2	2

Table G.1: Project hours per time period per team member data set

PT value	52	51	45	44	39	37	34	33	30	29	27	25	23	21	20	19	18	17	16	15	13
Occurance	3	3	1	2	2	1	1	1	2	1	1	3	3	2	1	1	1	4	1	1	3

PT value	10	9	8	7	6	5	3	2	1	0
Occurance	3	3	2	4	1	3	2	1	2	3

Table G.2: Project duration data set

Consultant\Time	**0**	**1**	**2**	**3**	**...**	**51**
0	0	0	0	0		0
1	8	8	8	8		16
2	6,4	10,4	12	12		21,6
3	32	32	32	32		0
4	0	0	0	0		0
5	4	4	4	4		40
6	3,2	3,2	3,2	3,2		40
7	12	20	20	20		24
8	8	8	8	8		40
9	8	0	0	0		40
...						
102	0	0	0	0		0

Table G.3: Consultant net available working hours per time period data set

H MANUAL CALCULATIONS SINGLE KPI EXPERIMENTS

We generate according to table 5.1, 2 instances for the single KPI optimization experiments. Since BE NL has the business rule to accept projects if feasible (so independent of KPIs), we start by identifying for each instance the projects that can be accepted based on the consultant availability and the project characteristics (project duration and project hours per team member). This identification leads to a list of accepted projects and the consultant(s) that can be assigned to these projects. In case multiple assignments can be made to a project, we check for each assignment possibility the effect on the single KPI value. We choose the assignment leading to the best value (lowest value for cost, closest value to zero for skill match, and highest value for utilization and satisfaction). We compare the manual calculated single KPI experiment values with the KPI values the C2Pa model came up with. In case both values are the same, the C2Pa model's correctness is verified. Table H.1 shows the manual calculated KPI values. To illustrate this verification process, we show the manual calculations for one of the two instances in Section H.1 until H.5.

Experiment	KPI value
single utilisation KPI	55.61
single cost KPI	127.00
single satisfaction KPI	6.40
single skill match KPI	2.00

Table H.1: Manual calculated KPI values for the single optimization KPI experiments

H.1 Possible assignments

Table H.2 shows the possible assignments for the projects. A consultant can only be assigned to one of the team member roles of a project. Since project 0 and project 3 only have 1 option for both the team member roles and both options are the same consultant, the projects can not be accepted since this would lead to an infeasible solution. Therefore, only project 2 is accepted. The only consultant that can be assigned to project 2 is consultant 9.

Project	Available consultants
project 0 team member 0	11
project 0 team member 1	11
project 1 team member 0	-
project 1 team member 1	-
project 2	9
project 3 team member 0	11
project 3 team member 1	11
project 4 team member 0	-
project 4 team member 1	-
project 5	-
project 6	-
project 7 team member 0	-
project 7 team member 1	-
project 8 team member 0	-
project 8 team member 1	-

Table H.2: Possible assignments to each project based on consultant availability

H.2 Best assignment(s) consultant-to-project assignment cost KPI

Table H.3 shows the job position and hourly cost for the consultants. Since only consultant 9 can be assigned to project 2, the weighted average hourly assignment cost will be equal to consultant 9's hourly cost which is 127.

Consultant	Job position	Hourly cost
Consultant 0	MA	115
Consultant 1	C	127
Consultant 2	C	127
Consultant 3	SC	140
Consultant 4	C	127
Consultant 5	C	127
Consultant 6	C	127
Consultant 7	SC	140
Consultant 8	C	127
Consultant 9	C	127
Consultant 10	MA	115
Consultant 11	C	127
Consultant 12	SC	140
Consultant 13	C	127
Consultant 14	C	127

Table H.3: The job position and hourly cost for the consultants

H.3 Best assignment(s) consultant-to-project utilization KPI

We calculate the average consultant-to-project utilization for every time period for every consultant as the already assigned hours of consultant i at time t plus the assignments of the model of consultant i at time t divided by the working hours of consultant i at time t multiplied by 100%. We use the average consultant-to-project utilization to calculate the total weighted average utilisation. We calculate the total weighted average utilisation by summing over all time periods the multiplication of the average utilisation of consultant i by the working hours of consultant i. These are then summed for all consultants and divided by the total working hours. This leads to a total weighted average utilisation of 55.61.

H.4 Best assignment(s) consultant satisfaction KPI

Table H.4 shows the required project skills for project 2. Project 2 requires skill 5, 14, 15, 18 and 21. Table H.5 shows consultant 9's satisfaction. Since we only have 1 project with 1 assigned consultant the weighted average consultant satisfaction equals the average satisfaction of consultant 9 to project 2. The average satisfaction of consultant 9 to project 2 is 6.4.

Project 2	Required skill level
Skill 0	0
Skill 1	0
Skill 2	0
Skill 3	0
Skill 4	0
Skill 5	1
Skill 6	0
Skill 7	0
Skill 8	0
Skill 9	0
Skill 10	0
Skill 11	0
Skill 12	0
Skill 13	0
Skill 14	1
Skill 15	1
Skill 16	0
Skill 17	0
Skill 18	1
Skill 19	0
Skill 20	0
Skill 21	1
Skill 22	0

Table H.4: Project 2's required skill levels

Satisfaction	Consultant 9
Skill 5	5
Skill 14	7
Skill 15	8
Skill 18	6
Skill 21	6
Average satisfaction	6.4

Table H.5: Consultant 9's satisfaction levels with respect to project 2's required skills

H.5 Best assignment(s) C2Pa skill match KPI

Table H.6 shows the required skill levels of project 2 and consultant 9's skill levels with respect to the required skills. Since project 2 is the only accepted project and consultant 9 the only team member of project 2, the average C2Pa skill match equals the C2Pa skill match for the assignment of consultant 9 to project 2. The C2Pa skill match for the assignment of consultant 9 to project 2 equals 2.

Project 2	Required skill level	Consultant 9’s skill level	Skill match
Skill 5	1	1	0
Skill 14	1	3	2
Skill 15	1	2	1
Skill 18	1	0	-1
Skill 21	1	1	0
		Sum skill match	2

Table H.6: The C2Pa skill match for the assignment of consultant 9 to project 2

I GOODNESS OF FIT TESTS

This appendix shows results of the goodness of fit tests on the input parameters for the experimental case.

I.1 Consultant skills

Fitting Results — MA

#	Distribution	Parameters
1	Binomial	n=3 p=0,25165
2	Geometric	p=0,55645
3	Poisson	λ=0,79710

Fitting Results — C

#	Distribution	Parameters
1	Binomial	n=7 p=0,17526
2	Geometric	p=0,43164
3	Poisson	λ=1,31680

Fitting Results — SC

#	Distribution	Parameters
1	Binomial	n=11 p=0,11061
2	Geometric	p=0,44574
3	Poisson	λ=1,24350

Figure I.1: Fitting results Poisson distribution for the skill levels of MA, C, and SC

Goodness of Fit - Summary — MA

#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	Binomial	0.05928	2	22.342	2
2	Geometric	0.13616	3	24.769	3
3	Poisson	0.04701	1	18.833	1

Goodness of Fit - Summary — C

#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	Binomial	0.09905	2	34.838	2
2	Geometric	0.14592	3	40.563	3
3	Poisson	0.07431	1	25.802	1

Goodness of Fit - Summary — SC

#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	Binomial	0.05175	2	19.629	2
2	Geometric	0.15008	3	28.849	3
3	Poisson	0.03766	1	18.037	1

Figure I.2: Results goodness of fit Poisson distribution for the skill levels of MA, C, and SC

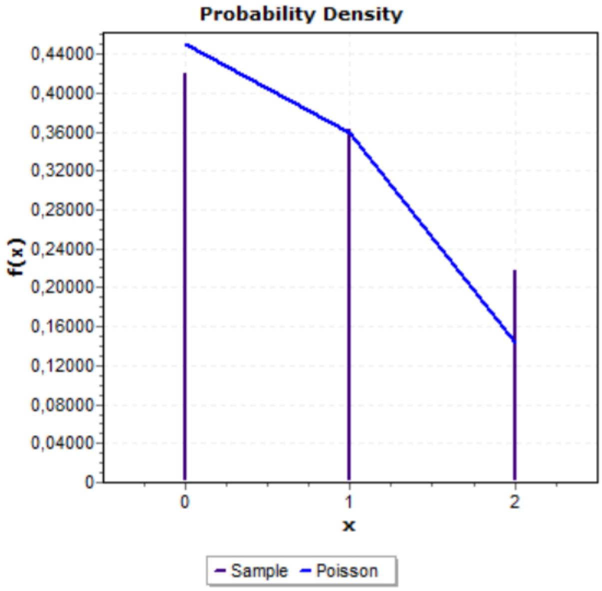

Figure I.3: Probability density function of the Poisson distribution for the skill levels of MA

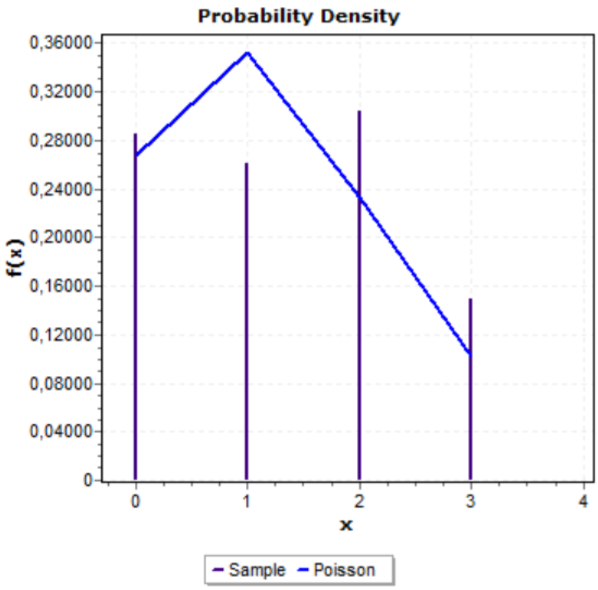

Figure I.4: Probability density function of the Poisson distribution for the skill levels of C

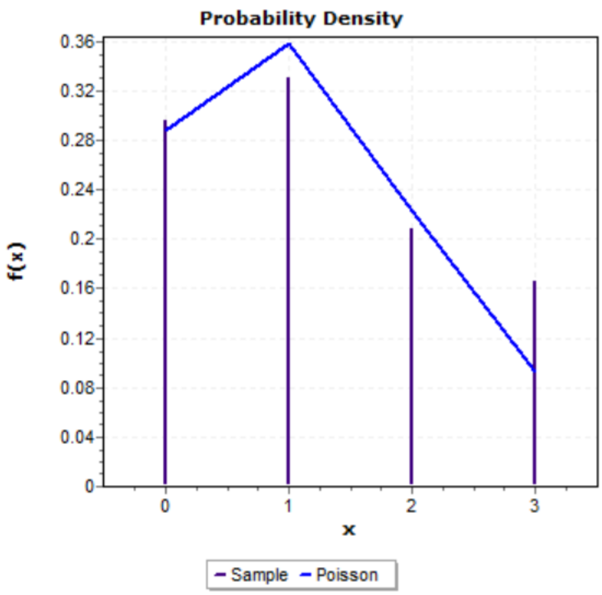

Figure I.5: Probability density function of the Poisson distribution for the skill levels of MA

I.2 Consultant skills

Fitting Results

#	Distribution	Parameters
1	Geometric	p=0,14896
2	Poisson	λ=5,71300
3	Binomial	no fit

Figure I.6: Fitting results Poisson distribution for the skill satisfaction

Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	Geometric	0,28414	2	71,63900	2
2	Poisson	0,08997	1	22,28300	1
3	Binomial	no fit			

Figure I.7: Results goodness of fit Poisson distribution for the skill satisfaction

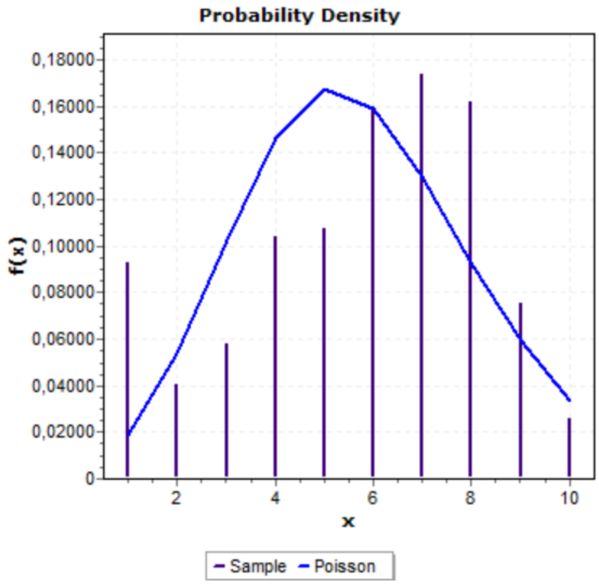

Figure I.8: Probability density function of the Poisson distribution for the skill satisfaction

I.3 Project hours per time period per team member

Fitting Results

#	Distribution	Parameters
1	Geometric	p=0,02890
2	Poisson	λ=40
3	Binomial	no fit

Figure I.9: Fitting results Poisson distribution for the project hours per time period per team member

Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	Geometric	0,31745	1	37,63100	1
2	Poisson	0,45808	2	65,27200	2
3	Binomial	no fit			

Figure I.10: Results goodness of fit Poisson distribution for the project hours per time period per team member

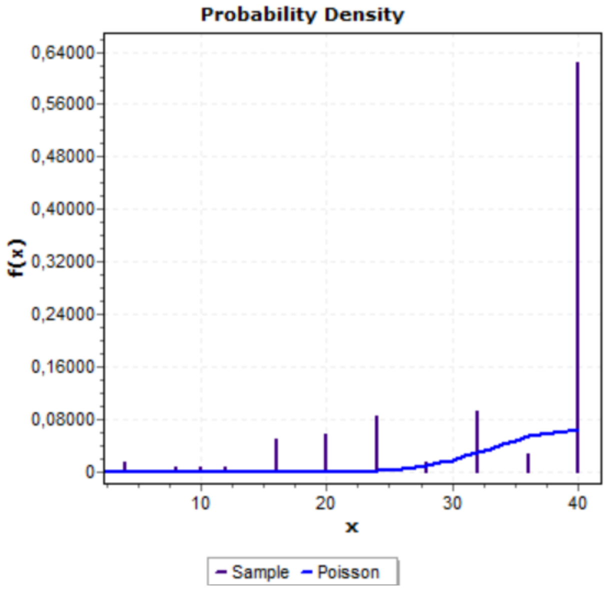

Figure I.11: Probability density function of the Poisson distribution for the project hours per time period per team member

I.4 Project duration

Fitting Results

#	Distribution	Parameters
1	Geometric	p=0,03379
2	Poisson	λ=28,59700
3	Binomial	no fit

Figure I.12: Fitting results Poisson distribution for the project duration

Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	Geometric	0,06868	1	0,76684	1
2	Poisson	0,46185	2	148,82000	2
3	Binomial	no fit			

Figure I.13: Results goodness of fit Poisson distribution for the project duration

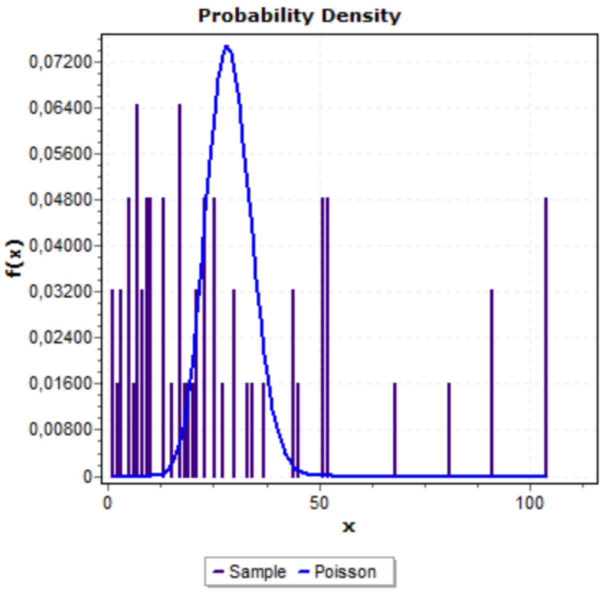

Figure I.14: Probability density function of the Poisson distribution for the project duration

I.5 Project skills

Fitting Results

#	Distribution	Parameters
1	Geometric	p=0.67427
2	Poisson	λ=0.48309
3	Binomial	no fit

Figure I.15: Fitting results Poisson distribution for the project skills

Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	Geometric	0.05332	1	98.741	2
2	Poisson	0.08844	2	83.1	1
3	Binomial	no fit			

Figure I.16: Results goodness of fit Poisson distribution for the project skills

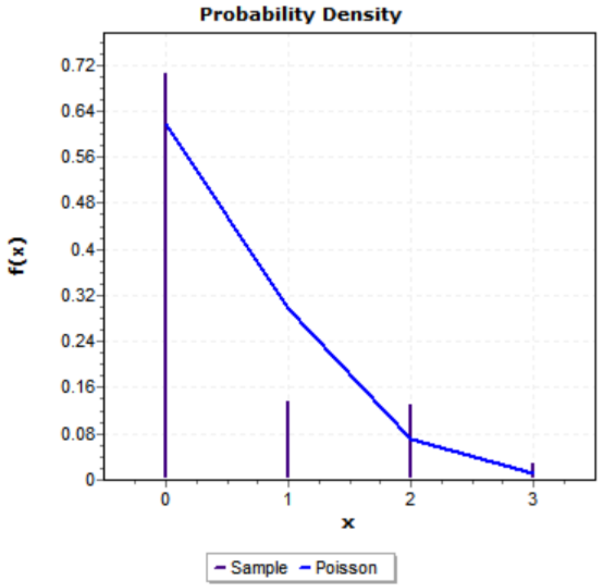

Figure I.17: Probability density function of the Poisson distribution for the project skills

J SIMULATED ANNEALING

Chapter 3 proved that the C2Pa problem (simulatenous multi-project scheduling and multi-skilled staffing problem) is NP-hard and that solving large and medium-scaled problem instances goes beyond the scope of exact algorithms. Increasing the C2Pa problem to all services lines therefore could create limitations for using the tool in terms of computational times. Therefore, we investigated the use of (meta)heuristics and hybrid approaches to find near-optimal solutions in polynomial time. For the simultaneous multi-project scheduling and multi-skilled staffing problem, the most popular methods in literature are Genetic Algorithm (GA), Simulated Annealling (SA), and Tabu Search (TS). Since SA is easily implemented and outperforms the other metaheuristics in both computational time as performance (Chapter 3), we opt for simulated annealing. This chapter therefore gives advice for implementing simulated annealing for the C2Pa model.

J.1 Simulated annealing algorithm

Subsection 3.4.3 discussed how simulated annealing worked. Algorithm 1 shows the pseudocode of SA algorithm.

Algorithm 1: Pseudocode simulated annealing

$T \leftarrow T_{start}$;
$Solution \leftarrow ConstructInitialSolution$;
$CurrentBest \leftarrow Solution$;
while $T > T_{stop}$ **do** ;
    for $m \leftarrow 1$ to $MarkovChainLength$ **loop** ;
        $NeighborSolution \leftarrow FindNeighborSolution(Solution)$;
        if $NeighborSolution < Solution$ **then** ;
            if $NeighborSolution < CurrentBest$ **then** ;
                $CurrentBest \leftarrow NeighborSolution$;
            end if;
            $Solution \leftarrow NeighborSolution$;
        else;
            if $RandomNumber \leq \epsilon^{\frac{CurrentSolution - NeighborSolution}{T}}$ **then** ;
                $Solution \leftarrow NeighborSolution$;
            end if;
        end if;
        $T \leftarrow \alpha \cdot T$;
    end loop;
end while;
$Result \leftarrow CurrentBest$;

J.2 Initialize solution

The pseudocode for the simulated annealing algorithm (Algorithm 1) shows that the algorithm needs a initial solution. We explore two different initial solution techniques to try to find the best initial solution technique for the SA of the C2Pa problem. We define best as the fastest and highest performing. The first technique is the random assignment technique. In the random assignment technique, we randomly pick a consultant and assign this consultant to a project team member. After all team member roles for all projects are occupied, we randomly assign for each of the required skills one of the team members. Furthermore, we let all projects start at their earliest start time. This random assignment technique is fast, but very unlikely to result in a feasible or optimal solution. The SA algorithm could therefore, take longer to converge and possibly have weaker performance.

The second technique is the constructive heuristic technique. The constructive heuristic technique starts from an empty solution and iteratively adds to this solution until all assignments and scheduling is done. To explore the impact of an feasible solution on the performance of the SA, we decide to create the constructive heuristic technique in such a way that this technique results in a feasible solution. For a solution to be feasible, the solution should satisfy all constraints. In the C2Pa model these are:

- a project starts in its time window
- all required project skills are distributed over the team members according to the project hours per team member roles
- consultants assigned to a project stay until completion of the project assigned to this project as the same team member role and to the same skills
- the availability of the consultant is respected

Algorithm 2 shows the pseudocode for a constructive algorithm that assigns in every increment one consultant to one or multiple required skills, and one team member role of one project while ensuring the constraints are met.

We calculate the objective function of the initial solution according to the MILP model (Subsection 4.1.2).

Algorithm 2: Constructive algorithm for feasible initial solution

for *project* $p \leftarrow 1$ **to** P **do**
for *team member* $m \leftarrow 1$ **to** m_p **do**
for *consultant* $i \leftarrow 1$ **to** m **do**
for *time* $t \leftarrow ES_p$ **to** LS_p **do**
if *consultant i has availability* **then**
Assign consultant i from t until $t + pt_p$ to team member m and to $st_{p,m}$ random skills of project p
Update consultant i's availability
if $m = m_p$ **then**
Next *project*
else
Next *team member*
end
end
end
end
No consultant is available for team member m of project p
end
end
return *Feasible initial solution*

J.3 Neighborhood functions

Next to an initial solution, the SA algorithm also needs neighborhood functions to seek the solution space for improvement. We explore seven different neighborhood functions to try to find the best neigborhood function for the SA of the C2Pa problem. These neighborhood functions are: skill swap, project shift, team member swap, replace consultant, add/remove assignment, combination of three neighborhood functions, and VNS.

J.3.1 Skill swap

The first technique is a random skill swap. This neigborhood function swaps one skill between two team members of the same project. Since all skills take the same duration this move will always satisfy the working hours constraint and improves or decreases the current assignment. This move impacts the current assignment by impacting the consultant skill satisfaction KPI and the C2Pa skill match KPI. Algorithm 3 shows the pseudocode for this neighborhood function.

Algorithm 3: Swap one skill between two team members of the same project

Input: *CurrentSolution*, the current C2Pa solution.
Output: *NeighborSolution*, the solution after applying the swap move.
$ProjectA \leftarrow$ Select one random project from $CurrentSolution$ where $m_p \geq 2$;
$TeamMemberA, TeamMemberB \leftarrow$ Select two random team members from $ProjectA$;
$ConsultantA, ConsultantB \leftarrow$ Retrieve the two consultants assigned to $TeamMemberA$ and $TeamMemberB$;
$SkillA, SkillB \leftarrow$ Select one random skill of $ProjectA$ to which $ConsultantA$ is assigned to and one for $ConsultantB$;
for t in project duration;
Swap $SkillA$ of $ConsultantA$ with $SkillB$ of $ConsultantB$;
end;
Calculate NeighborSolution;
Return $NeighborSolution$;

J.3.2 Team member swap

The second technique is the team member swap. The team member swap can occur within a project or between projects. In case the team member swap is within a project, the swap is more likely to be feasible since the consultant gains available time from unassigning from the current team member role which can be used for the potential assignment to the new team member role. Both team member swap cases impact all KPIs. Algorithm 4 shows the pseudocode for this neighborhood function.

Algorithm 4: Swap team members within and between projects

NOTE: This could create an infinity loop if no team member swaps are possible anymore. Do something to prevent this! Like counter that after starting again for X times the algorithm stops. Moreover, how to deal with the for loops. Project A has different time then Project B. Creating more loops???
Input: *CurrentSolution*, the current C2Pa solution.
Output: *NeighborSolution*, the solution after applying the swap move.
$ProjectA, ProjectB \leftarrow$ Select two random projects from $CurrentSolution$;
$TeamMemberA, TeamMemberB \leftarrow$ Select one random team members from $ProjectA$ and one from $ProjectB$;
$ConsultantA, ConsultantB \leftarrow$ Retrieve the two consultants assigned to $TeamMemberA$ and $TeamMemberB$;
$SkillsAssignedToTeamMemberA, SkillsAssignedToTeamMemberB \leftarrow$ Retrieve all skills assigned to $TeamMemberA$ and all skills assigned to $TeamMemberB$;
for t in $ProjectA$'s duration;
    Unassign $SkillsAssignedToTeamMemberA$ from $TeamMemberA$;
    for t in $ProjectB$'s duration;
        if project hours required for performing $SkillsAssignedToTeamMemberB$ fits within $ConsultantA$'s availability **then**;
            Unassign $SkillsAssignedToTeamMemberB$ from $TeamMemberB$;
            if project hours required for performing $SkillsAssignedToTeamMemberA$ fits within $ConsultantB$'s availability **then**;
                Assign $SkillsAssignedToTeamMemberA$ to $TeamMemberB$ and $SkillsAssignedToTeamMemberB$ to $TeamMemberA$;
            else;
                Reassign $SkillsAssignedToTeamMemberB$ to $TeamMemberB$;
                Randomly select new project for $ProjectB$ from $CurrentSolution$ and **reset loops**;
            end;
        else;
            Reassign $SkillsAssignedToTeamMemberA$ to $TeamMemberA$;
            Randomly select new project for $ProjectB$ from $CurrentSolution$ and **reset loops**;
        end;
    end;
end;
Calculate NeighborSolution;
Return $NeighborSolution$;

J.3.3 Add/remove assignment

The third technique is the add/remove assignment. The add/remove assignment either adds one or multiple consultants to the available team member role(s) of a project (only works for declined projects otherwise all team member roles are filled) or removes all consultants from all team member roles of a project (making a project a declined project). The reason why we choose to fill all team member roles is because we then remove the penalty incurred for declining a project. The reason why we choose to remove all consultants, is because when a project is declined we already get the penalty. So letting consultants remain assigned to a declined project, is therefore a waste of resources. Algorithm 5 shows the pseudocode for this neighborhood function.

Algorithm 5: Add consultant(s)/ remove all consultants to/from team member role(s) of a project

NOTE: This could create an infinity loop if no team member swaps are possible anymore. Do something to prevent this! Like counter that after starting again for X times the algorithm stops.
Input: *CurrentSolution*, the current C2Pa solution.
Output: *NeighborSolution*, the solution after applying the add/remove move.
$RandNumbr \leftarrow$ random(0,1);
$ProjectA \leftarrow$ Select one random project from $CurrentSolution$;
$EmptyTeamSlots \leftarrow$ Select the empty team slots of $ProjectA$;
$EmptyTeamSlotsNr \leftarrow$ Determine the number of empty team slots of $ProjectA$;
$AddConsultants \leftarrow$ Randomly select $EmptyTeamSlotsNr$ consultant(s) not in $ProjectA$;
$SkillsTeamMembers \leftarrow$ Select for each $EmptyTeamSlots$ the number of unassigned skills that correspond with the project hours of $EmptyTeamSlots$;
$DeleteConsultants \leftarrow$ Select all consultants in $ProjectA$;
if $RandNumbr \geq 0.5$ **then**;
    for t in $ProjectA$'s duration;
        if availability of $AddConsultants$ is respected when assigned to $EmptyTeamSlots$ **then**;
            Add $AddConsultants$ to $EmptyTeamSlots$ and $SkillsTeamMembers$;
        else;
            Randomly select new consultant(s) for $AddConsultants$ whose availability was not respected that are not in $ProjectA$ and **reset loops**;
        end;
    end;
else;
    for t in $ProjectA$'s duration;
        Unassign $DeleteConsultants$ from $ProjectA$;
    end;
end;
Calculate NeighborSolution;
Return $NeighborSolution$;

J.3.4 Project shift

The fourth technique is the project shift. The project shift is the easiest move for creating a neighborhood solutions to check if the consultant-to-project utilization KPI for the current solution can be improved. The project shift move creates neighborhood solutions by letting the project start earlier and later. The project still needs to be feasible meaning that this should happen within the starting time window. After each shift in schedule we check if the solution is still feasible by looking if the availability for the consultants is respected and if this is the case the new neighbor solution objective value is calculated. Algorithm 6 shows the pseudocode for this neighborhood function.

Algorithm 6: Shift the project to one time period earlier or one time period later

NOTE: This could create an infinity loop if no team member swaps are possible anymore. Do something to prevent this! Like counter that after starting again for X times the algorithm stops.
Input: *CurrentSolution*, the current C2Pa solution.
Output: *NeighborSolution*, the solution after applying the project shift move.
$ProjectA \leftarrow$ Select one random project from $CurrentSolution$;
$TeamMembersProjectA \leftarrow$ Select all team members from $ProjectA$;
for t in range(ES_p,LS_p);
Let $ProjectA$ start and end 1 time period earlier;
if availability of all $TeamMembersProjectA$ is respected **then**;
Calculate NeighborSolution;
else;
Let $ProjectA$ start and end 1 time period later;
if availability of all $TeamMembersProjectA$ is respected **then**;
Calculate NeighborSolution;
else;
Randomly select new project for $ProjectA$ from $CurrentSolution$ and **reset loops**;
end;
end;
end;
Return $NeighborSolution$;

J.3.5 Replace consultant

The fifth technique is the replace consultant move. The replace consultant move creates neighborhood solutions by removing a consultant from a project and assign another consultant to this project. After replacing a consultant the feasibility is checked by looking if the newly assigned consultant is respected. Algorithm 7 shows the pseudocode for this neighborhood function.

Algorithm 7: Replace a consultant on a project

Input: *CurrentSolution*, the current C2Pa solution.
Output: *NeighborSolution*, the solution after applying the replace consultant move.
$ProjectA \leftarrow$ Select one random project from $CurrentSolution$;
$TeamMemberA \leftarrow$ Select one random team member from $ProjectA$;
$ConsultantA \leftarrow$ Retrieve the consultant assigned to $TeamMemberA$;
$AddConsultantA \leftarrow$ Select a random consultant not in $ProjectA$;
$SkillsTeamMemberA \leftarrow$ Select the number of unassigned skills that correspond with the project hours of $TeamMemberA$;
for t in $ProjectA$'s duration;
if availability of $AddConsultantA$ is respected when assigned to $TeamMemberA$ **then**;
Unassign $ConsultantA$ from $TeamMemberA$ and $SkillsTeamMemberA$;
Add $AddConsultantA$ to $TeamMemberA$ and $SkillsTeamMemberA$;
else;
Randomly select new consultant for $AddConsultantA$ not in $ProjectA$ and **reset loops**;
end;
end;
Calculate NeighborSolution;
Return $NeighborSolution$;

J.3.6 Combination of three neighborhood functions

The sixth technique is combining three neighborhood functions into one. The reason for using a combination of three is because we have three decision variables and although most neighborhood functions impact all of these three, there are certain neighborhood moves which focus (slightly) more on one of the three decision variables. Furthermore, since testing all combinations of neighborhood functions is not possible within tbe time scope of this research, we decide to test one combination of three neighborhood functions which impact all decision variables and has the highest potential for delivering the best simulated annealing results. We think that combining the team member swap (neighbor move with highest impact on assignment decision variable), add/remove assignment (neighbor move with highest impact on decline/accept project decision variable), and project shift (neighbor move with highest impact onscheduling decision variable) is the most promising combination. Moreover, this combination provides a nice balance between exploration and exploitation, involves many constraints, and includes three very different neigbor moves.

To decide which neighborhood move we use, we draw a random integer between 1 and 3. 1 corresponds to team member swap, 2 corresponds to add/remove assignment, and 3 corresponds to project shift. Algorithm 8 shows the pseudocode for this neighborhood function.

Algorithm 8: Combination of three neighbor moves

Input: *Team member swap, Add/remove assignment, Project shift*: Import the three selected neighbor moves.
Output: *NeighborSolution*, the solution after applying the add/remove move.
$RandNumbr \leftarrow$ randint(1,3);
if $RandNumbr = 1$ **then**;
    Perform $Team\ member\ swap$ (Algorithm 4);
elseif $RandNumbr = 2$;
    Perform $Add/remove\ assignment$ (Algorithm 5);
else;
    Perform $Project\ shift$ (Algorithm 6);
end;
Return $NeighborSolution$;

J.3.7 VNS

The seventh technique is VNS. This technique uses similar moves as the second technique however these moves are not chosen according to a probability but dependent on k. k changes from 1 to 2, until 3 if the current solution is updated with a worse solution and resets to 1 if the current solution improves (1 for team member swap and 2 for add/delete assignment and 3 for project shift (Lalla-Ruiz et al., 2020). Algorithm 9 shows the pseudocode for this neigborhood function.

Algorithm 9: Variable Neighborhood Search (VNS) with Three Neighborhoods

Input: *IntialSolution, Team member swap, Add/remove assignment, Project shift*: Import the InitialSolution and the three selected neighbor moves.
Output: *NeighborSolution*, the solution after applying the VNS neighborhood function.
$CurrentSolution \leftarrow InitialSolution$;
$BestSolution \leftarrow CurrentSolution$;
$k \leftarrow 1$ Set initial neighborhood;
while *Stopping criterion not met* **do**
    if $k = 1$ **then**
        NeighborSolution $\leftarrow$ Apply $Team\ member\ swap$ to $CurrentSolution$;
    end
    else if $k = 2$ **then**
        NeighborSolution $\leftarrow$ Apply $Add/remove\ assignment$ to $CurrentSolution$;
    end
    else
        NeighborSolution $\leftarrow$ Apply $Project\ shift$ to $CurrentSolution$;
    end
    if *NeighborSolution is better than CurrentSolution* **then**
        $CurrentSolution \leftarrow$ NeighborSolution;
        if *CurrentSolution is better than BestSolution* **then**
            $BestSolution \leftarrow$ CurrentSolution;
        end
        $k \leftarrow 1$ Reset neighborhood when improvement is found
    end
    else
        $k \leftarrow k + 1$ Try the next neighborhood
    end
end
NeighborSolution = BestSolution;
Return NeighborSolution;

J.4 Other input parameters SA

At last, the SA algorithm also needs a starting temperature, stopping temperature, Markov chain length, and cooling schedule.

We choose the initial temperature (T_{start}) in such a way that almost every transition is possible to ensure high diversification at the start of the algorithm. This means that T_{start} is chosen such that the initial acceptance ratio is approximately 1 (Subsection 3.4.3). We set the Markov chain length according to the length of the number of neighbor-solutions. At last, we use a commonly used coooling schedule for the SA algorithm: $T_{K+1} = \alpha T_k$ (Rader, 2010).