Highlights

It's About Time: How To Study Intertemporal Choice in Systems Design

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- Intertemporal decision making is crucial for many software systems design problems.
- An empirical study of intertemporal decision making is presented.
- Software professionals vary in how they value outcomes across time.
- They identify intertemporal choices across all areas of software systems design.
- Theory and guidelines to study intertemporal systems design choices are presented.

It's About Time: How To Study Intertemporal Choice in Systems Design

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Abstract

Context: Decision making pervades software and systems engineering. *Intertemporal* decisions involve trade-offs among outcomes at different points in time. They play a central role in systems design, as recognised since the inception of the software engineering (SE) field. They are also crucial factors in the sustainability of design decisions. However, temporal decision making is not adequately understood in SE, while the field of Judgement and Decision Making (JDM) offers a vast array of empirical findings and research methods that could be utilised.

Objective: This article aims to examine how software professionals handle intertemporal choices; in what areas of software development such decisions can be found; and how systems design decisions can be characterised and studied as intertemporal.

Method: We developed a method to study intertemporal choice in SE, based on an initial set of psychological theory grounded in JDM. We instantiated the method in a study to elicit responses to an intertemporal choice task followed by a Cognitive Task Analysis (CTA) interview.

Results: We found that study participants overall displayed a tendency to discount future outcomes, but individual participants varied wildly in how

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they valued present vs. future outcomes. They indicated several locations in which intertemporal choices occur in everyday software development. Based on these findings, and by reconciling our initial theory with existing JDM theory and results, we further developed and refined our theory and study method into a framework for studying intertemporal decision making in SE.

Conclusions: To obtain a basis for more sustainable software systems design decisions, SE research should adopt a more comprehensive, detailed, and empirically consistent way of understanding and studying intertemporal choices. We provide suggestions for how future research could achieve practical methods that address essential characteristics of real-life systems design decisions.

Keywords: intertemporal choice, temporal discounting, judgement and decision making, naturalistic decision making, cognitive task analysis, psychology, human factors

1. Introduction

The life of a software system is full of trade-off decisions. Requirements engineers, architects, programmers, testers, user interface designers, project managers, and many other software experts must work in concert to navigate design options on different levels that shape the system they are making. In response to this reality, software engineering research and practice have developed sophisticated approaches to support and, in a limited sense, automate decision-making within specific areas of the profession.

Many trade-off decisions in systems design involve a dimension of central importance that is particularly difficult to grasp: *time*. Their outcomes are scattered in time: some of them are close, others distant. Decision making researchers call such trade-offs *intertemporal* [31]. Designers must judge not only *what* options exist, but also *when* they occur and *who* they affect. Long-term considerations have been discussed since the coining of the term "software engineering" (SE) and were part of the founding impetus of the field. They become increasingly urgent as a consequence of the ongoing trend of digitisation of society.

The intertemporal nature of SE choices may affect what is chosen in undesirable ways. A tendency to favour immediate outcomes over more distant ones may lead to favouring quick wins over options that look less attractive but are more sustainable. This has internal and external consequences for a software project. Internally, the deterioration of a design causes increased effort for future development and quality. Externally, consequences include negative effects for customers and society at large, depending on the kind of system being built.

In this paper, we explore the issue of complex software systems design decisions with implications over time through the psychological lens of *intertemporal choice*: 'decisions involving trade-offs among costs and benefits occurring at different times' [31, p. 351]. We discuss the nature of such decisions and introduce concepts from those scientific disciplines that have examined these topics since before SE emerged. To address the temporal dimension of decisions more wisely, we propose to first understand more about the decisions themselves as well as the complex cognitive and social decision-making processes that unfold when real-life systems design and development happens. Humans can, after all, successfully navigate very complex design spaces involving technical, social, temporal, and ethical dimensions. Knowing more about how that happens, and when and why the process might break down, will be crucial for the creation of novel approaches to decision-making in SE. We examine how time plays a role in design decisions in software projects, and we propose a characterisation of intertemporal choices that helps us understand and analyse their cognitive and social aspects. We conclude by mapping possible research directions that we may pursue to increase the understanding of intertemporal choice in software design decision-making across time. The direction taken here extends the existing significant research in SE on human factors (see, e.g., [8], [51], [74], and [27] for overviews of different areas) and opens a new direction of research with novel potential for improving how we design sustainable information and software technology.

2. Background

2.1. Decision-making across time in software engineering

Complex engineering decisions with many variables and parameters are at the heart of SE as a field. For example, this includes architectural trade-offs decisions [86, 41, 14, 91, 3, 28], Technical Debt management [52, 2, 24, 9], and software component selection [59, 38].

Intertemporal choices in which the outcomes are located at different future points occur in many areas of life. Pinpointing where they occur in systems design is not straightforward, but many decisions taken in system development have uncertain but far-reaching long-term effects. Many also involve trade-offs between uncertain longer-term effects and shorter-term effects. In SE, the decisions that are most explicitly intertemporal surface in Technical Debt management [52, 2, 24, 9], architectural trade-offs [86, 41, 14, 91, 3, 28], refactoring [1], software maintenance and sustainability [19], as well as in test automation, feature prioritisation, and project management decisions, as we established previously through a pair of systematic literature reviews [7, 5, 26]. These kinds of decisions all deal specifically with options that have outcomes at different points in the future. However, there may be other places too where intertemporal choices surface in less obvious ways.

Building on predecessor disciplines, SE methods rely on multi-criteria decision making methods including utility analysis and the Analytic Hierarchy Process [42, 72]. These mechanisms are used to effectively handle the uncertainty and complexity that arises from the interplay of many intersecting factors. Attention is now honing in on the cognitive aspect of decision making in such situations [86]. While the existing work on decision making in SE and its predecessor disciplines bring many valuable suggestions on how to effectively and efficiently compute a decision given complex parameters and probabilities, we recognise that the question 'how do human beings make such decisions' falls first and foremost into the purview of psychology and the social sciences. Similar to other human factors research in SE [51, 60], we therefore build first from a rigorous foundation based on reference disciplines such as psychology. These provide us with a vocabulary for being precise about the questions we ask.

2.2. The concept of intertemporal choice in reference disciplines

The reference discipline for decision making is of course the field of *Judgement and Decision Making* [44], which employs perspectives ranging from psychology and social psychology to behavioural economics, sociology, neuroscience and combinations thereof, such as neuroeconomics [55]. JDM typically locates its roots in Bernoulli's work that founded multi-criteria decision making but has incorporated a broad range of disciplinary views over the decades [43].

In SE and other fields, the terms *choice* and *decision* are sometimes used interchangeably. But it is worth paying attention to the nuances with which reference disciplines differentiate between these key terms.

- A *decision* arises in a situation in which someone could conceivably make different commitments on how to proceed. In naturalistic decision making, a decision is defined as "committing oneself to a certain course of action" [53]. We follow many JDM researchers in taking the encompassing perspective that a decision is a "conclusion or resolution reached after consideration" [65].

- A *choice* is a specific *type of decision* where distinct options exist from which a selection has to be made. In other words, a choice is the "act of selecting or making a decision when faced with two or more possibilities"[64].

- *Judgement* is broader. For example, when a person faced with a choice between two options rejects the framing and generates a third option to pursue, they have exercised judgement in reflecting on the boundaries of the presented decision and have made a different decision (commitment). In other words, judgement is "the ability to make considered decisions or come to sensible conclusions" [66].

It is important to note that these distinctions, while established in the reference disciplines of JDM, are not standard in SE. Instead, the prevailing view is narrower, based on only some areas that investigate decision making from a certain perspective. In Decision Analysis and Multi Criteria Decision Making, a narrow definition of decision making as choice – as "selecting one option among possible alternatives" – has been so dominant over the broader cognitive, psychological and social reality of decision making that the concept of decision making collapses into choice. As a consequence, some have questioned whether this concept is in fact relevant in software development – for example, whether programmers really make explicit 'choices' [71]. In reality, however, decisions often involve the creative development of new options and the re-examination of what comprises the situation. At the same time, they often do not involve *choices between options* [47]. This may appear counter-intuitive, but a commitment to action can be made, and often is made, without comparing multiple options.

Correspondingly, this article takes the encompassing definition of decision making from the JDM literature and uses the terms as defined above. However, we use the term choice to mean decision in one case: decisions that involve trade-offs between outcomes occurring at different points in the future. These are called *intertemporal choices* [31, 54], and constitute a central topic in JDM. The term intertemporal decision would perhaps be more accurate, but since the term is already established, we make this exception to be consistent with terminology in JDM and behavioural economics. Still, we speak of intertemporal decision making when referring to the activity of making decisions of an intertemporal nature.

Intertemporal choices are often studied in terms of the extent to which time changes the subjective valuation of an outcome. The degree to which an increase in time changes the valuation a decision maker places on an outcome is called *temporal discounting*. For example, a person who is indifferent between receiving \$100 in one year and receiving \$100 in two years would be said to exhibit no discounting, whereas someone who would require an additional \$100 to be indifferent to postponing the receipt of money by a year would be said to have a *discount rate* of 100% for that year. Researchers investigating intertemporal choice have noted that "most – if not all – choices that individuals and organisations make in the real world are intertemporal" [78]. It follows that many, if not most, software design choices are, too. SE decisions that are most explicitly intertemporal include Technical Debt management, architectural trade-offs, refactoring decisions, test automation, feature prioritisation, and many project management decisions [7, 26].

A wealth of research exists on intertemporal choice [54], but within the context of SE, it is a new concept [5]. Most theories, methods and studies are based on the idea that discounting exists and that it can be expressed as a mathematical model of valuation as a function of the time horizon. For example, the dominant model of *discounted utility* proposed by Samuelson [73] assumes that the discount rate is constant in time and models the future value FV as a function of the earlier (often present) value PV and the time between the two options t. In the case of discounted utility, the simplest model, the annualised continuously compounded *discount rate* DR_c [73] is constant: $FV = PV \times e^{DR_c \times t}$.

Because many studies observed that participants' choices are not well described by this exponential curve [31], other models have been developed and evaluated [56, 34, 31]. For example, in *hyperbolic discounting*, the discount rate decreases over time, with the rate of decrease in turn decreasing over time [69]; and the Area Under the Curve (AUC) provides a compound measure of the aggregate amount of discounting observed in an individual or a sample over the entire range of time periods [61].

Real-life intertemporal choices can be explicit and salient in the decision-maker's mind, such as the choice of whether to buy a specific health insurance; vague and open-ended, such as the decision of how to spend the weekend; or habitual, such as always buying a doughnut with the morning coffee on the way to work. It is usually not straightforward to tell what the best decision would be, and with varying individual characteristics, different persons will choose differently. Nevertheless, a general tendency is for humans to favour positive outcomes that are more immediate. A positive discount rate is common across experiments in many fields, meaning that in general, people tend to perceive outcomes further into the future as less important than more immediate ones [31].

Decisions do not happen in a vacuum, and the context in which decisions are made and the way that options are presented affect the decision outcome. The *choice architecture* concept describes how available options are presented to decision-makers, including factors such as layout, sequencing, and range of choices [81]. Altering such factors can nudge decision-makers towards certain choices and behaviours [80] and may interact with temporal aspects of the decision. Choice architecture in turn must be considered as part of the larger context of decision making, which includes such as aspects as team roles and group dynamics as well as organisational policies, incentives, norms, and values. In JDM, the entire system of these elements is referred to as the 'macro-cognitive' system of decision making (c.f. [46, 75]).

In summary, decades of intertemporal choice research in these reference disciplines have resulted in sophisticated study designs to elicit discount rates [15] and explore the many cognitive factors involved in preference construction and choice. Researchers have elaborated and compared several models to represent discounting behaviour over time; identified a "spectacular" range of individual behaviours in different studies [31]; explored questions such as the differential discounting of losses, gains, and 'mixed outcomes' that combine losses and gains [78]; and questioned whether the standard model of intertemporal choice based on quantitative discount rates over time is an empirically valid description of how the human mind perceives and values time [90]. These frameworks and methods provide a rigorous foundation for the study of intertemporal choice in systems design.

2.3. Intertemporal choice in SE

When we consider SE decisions *as intertemporal choices*, many questions arise. From this perspective, how software professionals actually make intertemporal design decisions is not at all clear: The question has only recently begun to attract attention in SE [89, 82, 86, 7, 5].

Excessive temporal discounting can cause significant long-term harm, so understanding discounting in software development may provide a key to better long-term outcomes. Long-term perspectives have often been advocated for [67, 62, 91]. For example, the focus of technical debt on 'expediency' [57] already emphasises the costs of short-term thinking. Even more importantly, short-term thinking can lead to harmful outcomes for stakeholders and society at large.

In a recent study [6], replicated in several countries [26], we examined whether software developers discount future outcomes. We found extensive temporal discounting: To regard a positive uncertain future outcome (effort savings) as equally valuable as a comparable closer outcome, participants in all cohorts required additional benefits that exceeded the effects of financial interest rates by orders of magnitude. But just as interestingly, the study also identified striking differences in individual preferences and found that developers with more breadth of experience discounted less.

3. Methods and Contributions

3.1. Research Questions

Our aim is to better understand the social and psychological dynamics at play in intertemporal software design decisions. This study addresses the following research questions:

RQ1: How does temporal distance affect software professionals' choices?

RQ2: Where do intertemporal choices occur in systems design practice?

RQ3: How can we characterise intertemporal choices in systems design?

To address these questions, we present a method for studying the behavioural and psychological aspects of what choices people make and how, and we instantiate it in an empirical study. Our method poses an intertemporal choice task in a familiar and often-occurring software project management task: that of choosing between work with benefit in the short term and long term. The method then uses this task as a probe for inquiring where and how intertemporal choices surface in our participants' work. This allows us to look for other activities where intertemporal choices occur. In the analysis, we abstract our results into a framework for guiding future studies on intertemporal choice in systems design. This section covers the design of the method, while Section 4 covers the study design using that method and Section 5 presents results from that study. The materials used in the method are available online[**?**].

3.2. Method: Cognitive Task Analysis

To examine how software professionals make judgements and decisions that involve trade-offs in time between uncertain future outcomes, our method is structured around an intertemporal choice task that performs two roles:

1. It elicits an intertemporal choice response from each participant.

2. It serves as a probe for a subsequent interview that explores what other intertemporal choices the participants face in their daily work and how they reason about them.

The method is designed to support researchers in exploring the range of reasoning mechanisms and heuristics in their participants' 'cognitive toolbox' [32]. For this reason, it is based on Cognitive Task Analysis (CTA).

CTA studies cognition in a real-world context [16] and has been applied in countless domains involving skilled expert performance, including medicine, emergency response teams, management, the military, and engineering [76, 36, 16]. It has come to describe a wide range of techniques for *knowledge elicitation*, *data analysis*, and *knowledge representation*. For each core aspect of CTA, techniques include methods known in other contexts, such as semi-structured interviews, Q Sort [10], or Repertory Grids [20, 11]; a range of methods specifically developed within CTA, such as Critical Decision Method [50], Critical Incident Technique [30], and Interacting Cognitive Subsystems [4]; and methods that originate within the practice of CTA and have found widespread adoption outside, such as concept mapping [63].

In SE, CTA techniques such as verbal protocol analysis [23] have been used to gain insights into how cognitive biases may impact the performance of software professionals [37]. For example, in a study on the relationship between pair-programming, cognitive biases and productivity, Jain et al. [39] found that novice and experts software developers are significantly affected by confidence bias, which reduces their productivity.

3.3. Task Design for intertemporal choice studies

To construct a study design for intertemporal decision making that allows us to evaluate how temporal distance affects preferences and choices, we turn again to the reference disciplines that have empirically studied intertemporal choice for decades [31]. A central issue is how to design the *task* that is used to prompt participants to make an intertemporal choice.

Many *task designs* have been proposed to uncover and quantify temporal discounting. Most present a specific, abbreviated situation and elicit a response from participants. That response is used to construct a representation of their time preferences and establish if, and how much, they discount over time [31]. A comprehensive comparison of methods is provided in Hardisty et al. [34].

The most frequently used study designs use either a *choice* task that asks participants to decide which of a set of alternatives they prefer [15, 35], or a *matching task* that requires participants to provide a number, typically the number at which one option becomes equally valuable as another one [79, 90]. Following this approach, our first empirical study on intertemporal choice in SE [6], replicated in several countries [26], employed a matching task combined with shifting time frames to establish, for each participant, their temporal preferences for a set of time frames ranging from 1 to 10 years. This is a well-established study design adopted from behavioural economics [31, 34].

In the task design used in this article, adopted from our previous study, we examine whether software developers discount future outcomes in a project management scenario. We ask participants to indicate the time savings they would require to regard an uncertain positive outcome at different times in the future (potential effort savings) as equally valuable as a comparable closer outcome (feature development). By asking participants to identify the threshold point at which the more distant outcomes is equal to the closer outcome, we can establish quantitative measures of the effect of time on their preferences.

The task design consists of two stages. First, a decision-making scenario is presented for a project currently in progress. Following the scenario description, participants see two options: 1) spend effort earlier on implementing a planned feature (a short-term option); or 2) spend effort to integrate a software library with potential long-term benefit in terms of reduced maintenance effort. The participants' task is to specify how many days of effort savings they would require to prefer the second, long-term option over the first, short-term option. Following best practice in JDM, the uncertainty of the outcome is fixed at 60% probability to minimise additional discounting due to a lack of precise information on the degree of uncertainty [31]. The response is used to establish a baseline preference (present value, PV) free of priming from the consideration of different time-frames.

Second, the scenario is presented again with several different project time horizons. This is the step shown in Figure 1. The baseline answer from step 1 is used as the *present value* – the baseline is compared against the other values to assess discounting. As a result, participants are actively asked to consider what difference time makes for their preference.

The outcome of such a task is a series of data points that can be used to plot the effect of temporal distance on participants' preferences, compute discount rates if desired, and measure in more general terms the temporal attitude of decision makers [15], as we previously demonstrated [6, 26] and will present in Section 5. When this task gets incorporated into a CTA study, however, it becomes the object of continuous observation and the critical incident that can be studied and examined.

Imagine the following scenario happening in the company you currently work in.

You are working on a project that delivers new functionality for a software system that directly affects end customers. It's the end of the week, and you are ahead of schedule in the current iteration. You will soon meet your team and product owner to discuss plans for the next week. You are expected to suggest what you should do during the next week. You have to choose between two options:

Option 1: Implement the next feature from the project backlog. The feature was originally meant for the following iteration. The feature is estimated to require five person days of effort.

Option 2: Work on a task that is not in the project backlog, but that has been discussed before. This task is to integrate a mature and well-tested library that adds no new functionality but could save some effort over the duration of the entire project. The chance of saving the effort is estimated to be 60% (with a 40% chance that the library will not result in those savings). The integration is estimated to require five person days of effort.

The project is 6 months long and has been going for three months.
How many days of effort savings would you require to prefer recommending Option 2 over Option 1?
________ days of effort

The project is 1 year long and has been going for three months.
How many days of effort savings would you require to prefer recommending Option 2 over Option 1?
________ days of effort

The project is 2 years long and has been going for three months.
How many days of effort savings would you require to prefer recommending Option 2 over Option 1?
________ days of effort

The project is 3 years long and has been going for three months.
How many days of effort savings would you require to prefer recommending Option 2 over Option 1?
________ days of effort

The project is 5 years long and has been going for three months.
How many days of effort savings would you require to prefer recommending Option 2 over Option 1?
________ days of effort

Figure 1: Intertemporal choice scenario and decision tasks (excerpt from questionnaire; version with work consequences for the participant themselves or their team).

4. Research Design and Analysis

4.1. CTA Study Design

The method described above provides a template for CTA studies of intertemporal choice in SE. The task serves as a probe – the 'critical incident' used for subsequent introspection and reflection. We rely on a probe because the conceptual framing of decisions *as intertemporal* is not common in practice (yet).

To instantiate this method in a study, we adapted our previous intertemporal choice study [6, 26] and embedded it into the CTA study protocol. Whereas participants in the original study answered an online survey on their own, we now had participants answer the survey with researchers present to observe them and collect data on how they reasoned. The present study can be understood as an operational, changed-protocol, changed-operationalisations, changed-populations, and changed-experimenters replication [33] with the addition of a qualitative framing. The CTA study thus uses the original, quantitative study as the incident and trigger for the cognitive activity we aim to examine. Materials and details of the study design, including coding schemes and examples, are available as supplementary material [**?**].

The incident was represented by the questionnaire discussed above (Figure 1). The purpose of the questionnaire is to provide the participants with a decision-making scenario to trigger their cognitive activity and to provide quantitative means of assessing the extent to which they would discount future choices. We based the questionnaire on the original study [6, 26]. We altered the time horizons to correspond more closely with project durations that the participants could encounter in their work. Finally, the questionnaire ended with demographic background questions.

Extensive guidance on how incident-focused interviews should be designed, conducted, and analysed has been collected [16, 76] and informs our research design.

Each session started with an introduction and verification of informed consent, followed by the participant receiving a paper questionnaire with a set of decision-making tasks (explained in the following section). The participant was asked to think aloud while reading and answering the questionnaire tasks. Once the tasks were completed, the researchers asked cognitive interview questions to gain more information about how the participant had reached the task answers. The sessions were recorded for later analysis, and throughout the sessions, the researchers took notes of their observations. Each session had one or two researchers present; guiding and note-taking were shared in some sessions. Each session was roughly one hour in length. At the end, participants filled in background information on themselves. In this paper, we utilise data from the post-task interview. The task served as a probe which helped participants recall similar episodes which could reveal where and how intertemporal choices occur in their work.

4.2. Participants and Implementation

We invited employees in three companies to participate in the study. Two of the companies remain anonymous in this paper.

S4N (*Company A*) is a Colombian software development company with offices in Bogotá, Medellín, and Seattle, USA, with more than 250 employees and more than 150 software products deployed in industries such as retail, airlines, insurance, and banking. In August 2021, S4N was acquired by EPAM Systems, Inc. [22], a leading digital transformation services and product engineering company. The data collection had been completed prior to the acquisition.

Company B, based in Greece, is a leading European IT solutions and services group with presence in multiple countries, employing more than 2,000 professionals. The company develops products for banking, law and customs, security and taxation, transportation, telecommunications, and healthcare sectors.

Company C is a Swedish publicly traded provider of accounting, invoicing, sales support, and payroll administration for small- and medium-sized companies. It has over 270 000 customers in Sweden and close to 300 employees.

All data collection sessions were conducted on site in closed, quiet rooms by researchers fluent in the participants' native languages (Spanish, Greek, and Swedish, respectively). The participants volunteered and were not offered incentives or rewards.

51 participants from the three companies (A: 20, B: 8, and C: 23) provided data for the study. There were 17 (33%) female and 32 (63%) male respondents; 2 (4%) did not provide gender information. The participants were between 21 and 47 years old (MD: 31, SD: 7.05). Data cleaning removed one missing interview and one missing set of quantitative responses.

4.3. Data analysis

The range of collected data include 30–90 minutes of recordings per participant, the quantitative responses to the questionnaire, interview transcripts, and the interviewers' observations and notes from the session. We examined the quantitative data to yield a categorization of participant behavior according to high-level patterns. The qualitative data, and second-order notes taken while analysing the session notes and transcripts, were further analysed to locate examples of situations with similarly temporal decisions that they were reminded of. We combined the individual findings to yield a higher-order descriptive framework of intertemporal choice.

4.3.1. Quantitative analysis of responses

For the quantitative analysis, we examined the choice task and demographic data using statistical methods to obtain measures for the amount of discounting among the participants. We calculated the overall discount rate using the area under the curve for the empirical function, i.e., the answers provided by the participants for each time horizon in the task, adjusted for the 60% probability given in the task, as done by [26] and documented in [25]. Because we allowed participants to specify that they would always choose a future option for all time horizons, our task data includes three answers with zero days for all time horizons. In the statistical calculations, we assumed that they were indifferent and constant in their discounting (i.e., their empirical function was set to 1 for all time horizons to allow calculations with the empirical function as divisor to work).

The choice of the exponential model was based on it being used in the original study [6, 26], as well as the lack of evidence for model choice in the field. The exponential model is commonly used in the intertemporal choice literature [34], is easy to calculate and replicate, and is sufficient to determine the degree of discounting. AUC was chosen based on its theory-neutrality [61], a desirable characteristic in the absence of evidence for model choice, its suitability for providing a comparable measure of total discounting for a participant, as well as its ease of calculation and replication.

We used descriptive statistics to examine the demographic data and describe the sample. We used boxplots to gain an overview of the distribution of the time-savings required by participants to choose the long-term option. We plotted the median discount rate against the time horizon options to examine the overall tendency. We also plotted individual discount rates against the time horizon to examine individual differences. All analysis code is included in the supplementary materials.

4.3.2. Qualitative analysis of interviews

The qualitative component of analysis consists of several related aspects. Note that we do not use the task recordings in this paper but focus on the interviews.

The interviews were recorded, transcribed by native speakers on the author team, and coded. For language reasons, coding was split with partial overlaps, maximizing how we deployed the language competences of the team. That means that the analysis was done on the originals for the Spanish and Swedish, and on translated transcripts for the Greek interviews. Spanish interviews were coded by one author and reviewed by the two senior authors fluent in Spanish. In this iterative process, we discussed and refined codes and their definition in a codebook in detail until consensus was reached. Greek interviews were then translated to English and coded by the same two authors; Swedish interviews were coded last, by one senior author. All quotes were manually translated by a native speaker of the origin language.

In the interviews, we asked our interviewees explicitly for situations of similar kind than our task to address RQ2. Careful to stay away from overly specific and leading language, we stated our interest in identifying "scenarios where there is this kind of future outcome that has to be considered" and asked them "help us pin down some examples of those kinds of situations'. We coded all interviews to identify (a) 'similar situations', broadly construed, (b) 'intertemporal choice' situations that are explicitly about temporal trade-offs, and (c) whether overall our interviewee recognized intertemporal choice situations in their work. For a full tabulation, see supplementary materials.

To identify where intertemporal choices occur in our participants' work (RQ2), we reviewed all these instances, and more broadly all interviews as a whole. In our participant's memories, similar to other cognitive interviews, a general recognition of semblance is often followed by some probing, which can trigger a sequence of related events, some of which more concrete than others. In our interviews we gain glimpses into stories and follow up on those that appear promising. We pick and report on example instances here because they represent situations that are

1. explicitly intertemporal (i.e. the interviewee describes them as having outcomes occurring at different points in time),
2. described in enough detail to narrate them in the article as a vignette, and
3. refer to concrete software engineering topics such as testing, project management, architecture, etc.

The identified concrete instances of intertemporal choices were organized into logical groups for the purpose of presenting them in Section 5.2. The chosen examples were selected not for their representative coverage or frequency, but for their value in explaining categories and illustrating salient aspects of *how SE categories* such as quality assurance or technical debt *bring forth intertemporality.* We do not provide frequency counts for these examples because there is no fixed threshold that defines at which point a participant's memory of a work situation and its semblance to intertemporal choice turns into a concrete experience. The overall assessment, whether or not each interviewee recognizes *some* intertemporal choice situations in their work life, is a holistic judgment that considers all parts of the interview and their dynamic evolution as a whole.

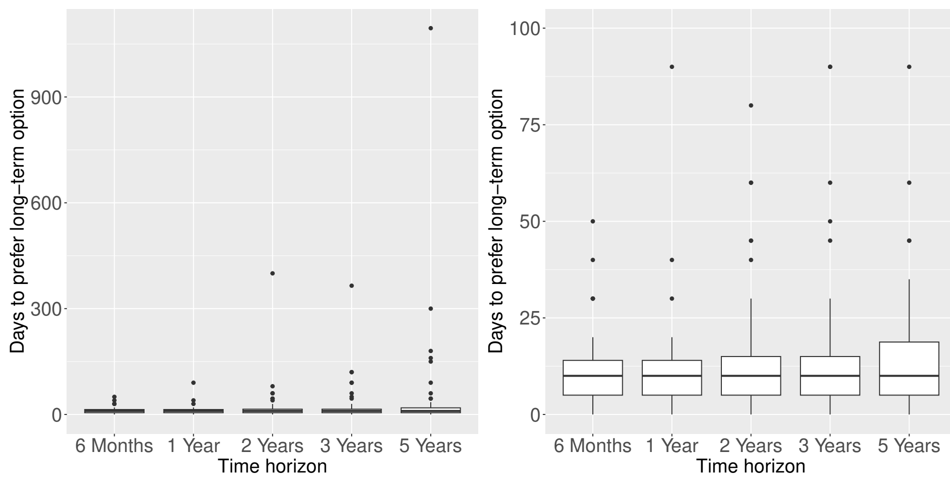
To characterize intertemporal choices in SE (RQ3), we used cues from the structure of the examples to characterize the *type* of situation *as intertemporal*, generalizing from situational features as well as prior literature in SE, JDM, and intertemporal choice. For example, when it comes to bug fixing, it is established that bugs are associated with severity, cost, and ripple effects, and relevant management concepts include cost estimation, risk management, prioritization, milestones, and project schedules. Temporal dynamics become visible in how these concepts relate to each other in concrete instances. This iterative process of cycling between theory and data in interpretation is typical for the analysis of qualitative cognitive interviews (Klein).

5. Results from the Study

In this section, we first examine the occurrence of temporal discounting. We show that despite an aggregate trend to favour more immediate outcomes, our participants vary in interesting ways in whether and how they discount future outcomes. We then identify examples of real-life situations where intertemporal choices occur and organise the examples into areas, providing an answer for how intertemporal choices manifest in systems design. We provide details of the research instruments, quantitative data from the intertemporal choice task, and examples of coded qualitative interview data as supplementary material [**?**].

5.1. Some software professionals exhibit temporal discounting, others don't (RQ1)

We first ask to what extent software developers exhibit temporal discounting at all. Figure 2 shows participants' responses across different time horizons at which potential future effort savings could be obtained in our



(a) Full data for all participants ($n = 50$). (b) Zoomed view with outliers omitted.

Figure 2: Results from our study on intertemporal choice in software projects, a replication of two previous studies [6, 26]. The figures show the distribution of time savings (days) to prefer a long-term investment, for different project time horizons. The left figure (a) shows the wide variance in discounting. Outliers above 100 days are omitted from the zoomed figure on the right (b) to focus on the main effect.

scenario (6 months, 1, 2, 3, and 5 years). For each time horizon, the participants were asked to indicate how many days of effort savings it would take for them to prefer the potential future savings over getting the nearer benefit. The responses show striking variance and a clear upward trend across time. The trend is similar to, but less pronounced than in our previous studies [6, 26].

For the intertemporal analysis, the first response for six months was used as the present value (PV) and normalised to 1, and the response for years one and beyond were set to the ratio between PV and the future value for each scenario. This allows us to calculate how a difference in temporal distance affects the participants' responses. To understand the kinds of temporal discounting behaviour, consider the three response patterns shown in Figure 3. For a participant indifferent to changes in time, the normalised ratio stays constant across time horizons. For a participant whose valuation changes with increased time, the curve deviates from 1. A downward deviation indicates temporal discounting: they prefer options with nearer outcomes. An upward deviation indicates a preference for more distant outcomes.

If we want to quantify the overall amount of discounting exhibited per

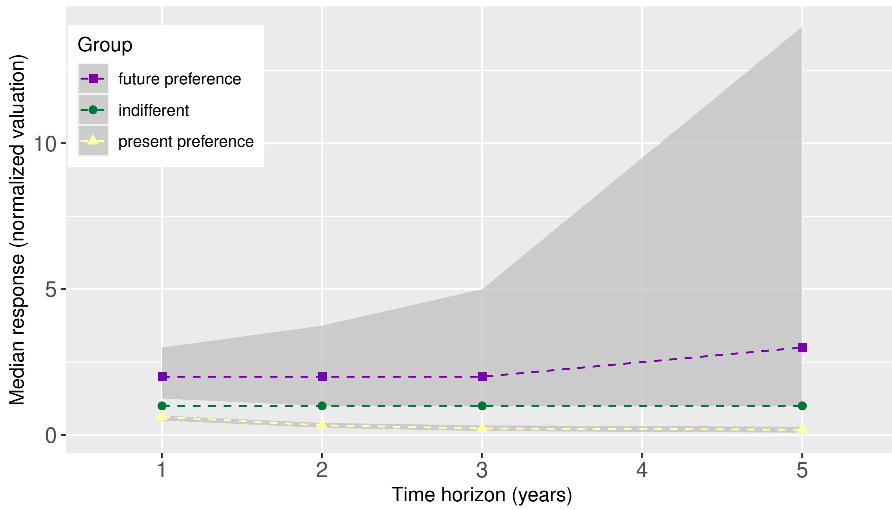


Figure 3: Future preferences ($n = 11$), present preferences ($n = 18$), and indifference ($n = 21$) appear when examining normalised responses to a project-level intertemporal choice scenario, split into groups by overall individual discounting. The grey area represents a 95% confidence interval.

participant across all time horizons, we can measure the area under the curve (AUC). In this case, with four curve segments, the AUC for an indifferent participant will be 4. An AUC above 4 indicates a *future preference*: the participant would, overall, prefer to wait for future benefits. An AUC below 4 indicates *temporal discounting*: the participant would, overall, prefer nearer benefits. An AUC of four is the line of *temporal indifference*.

As our analysis shows, we observed extensive temporal discounting in about 40% of participants, but also striking differences in individual preferences. About 40% of participants remained indifferent to changes in time, and over 20% exhibited a future-oriented perspective.

Figure 4 plots AUC per company and shows some striking patterns. There is no participant with future preference in the Greek sample, while the Swedish sample exhibits a very large range (additional outliers at 50 and 28 are omitted for visual clarity). While the limited data and the complexity of the situation prevent us from deducing simple causal factors to explain the comparisons across cohorts of this replication, it is interesting to note that this replication varies from previous populations in dimensions of culture (our participants come from three companies and three countries, one in the global south) and roles (this replication involves professionals while a previous replication involved students [26]). As in previous replications,

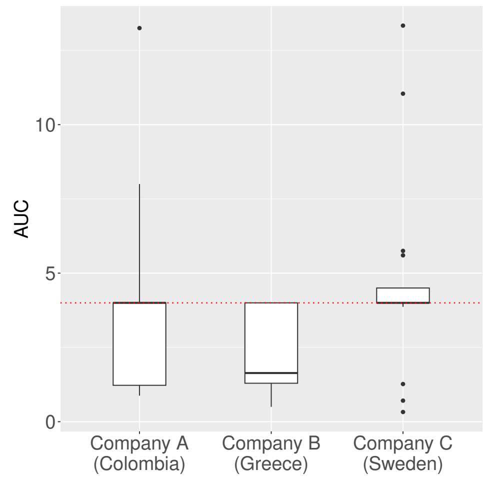


Figure 4: Temporal preferences quantified by AUC per company. Two outliers above 20 are omitted to highlight the main effect.

no correlations were found with respect to age and other demographic variables. This highlights the importance of gaining a situated understanding of individual differences in preferences and reasoning. We will return to this issue in the discussion.

5.2. Many situations in systems design involve intertemporal choices (RQ2)

Do professionals think that their work contains intertemporal choices? Yes, in the interviews, all but two of fifty study participants readily identified experiences they had encountered which resembled the intertemporal nature of the scenario we presented. They provided numerous examples from a range of domains that illustrate how intertemporal choices surface in their work. Some examples remained more abstract or somewhat vague, while others led to detailed stories and memories of recent incidents. Below, we review each identified domain and present a selection of examples that best illustrate how intertemporal choices manifest in our participants' professional practice. The purpose is not to exhaustively list all possible intertemporal choices in systems design, nor to make claims about how frequent or significant they are, but rather to show where they occur and how we might recognise them.

5.2.1. Product Development considers multiple time scales

Many examples referred to the strategic and operational choices made in product development, iteratively balancing competing demands and priorities that evolve on different timescales.

Feature development and prioritisation are intertemporal choices because they locate the realisation of various expressions of the organisation's values and goals at varying points in the future. The immediate concerns of satisfying customer needs is considered in relation to longer-term concerns about where the company wants to be in the future. For example, novel features are often considered in terms of their benefits and the costs to implement them. However, they may also incur maintenance and support costs that will only be realised in the long run.

> ... it is very difficult to weigh [feature ideas and improvements] against each other. You have to try to put them against each other a bit. That is something that often ends up being part of my role. (Product Owner, Company C) (1)

Prioritising a backlog similarly involves trade-offs between tasks with differing effort estimates and dependencies. The company may also have a longer-term perspective on building a specific customer segment or view a feature as incompatible with the long-term product vision.

> Let's say that sales have received five different orders. [We would ask them to] discuss and prioritise: which order do you think is most important [to] get these features [in]? You have to look at the effort as well. A feature may be small, [it] could be implemented in two weeks, and it can give us many new customers. Another feature might be huge or completely outside our target group ... Or we might see that this feature [leads in a direction we don't] want to go ... it leads to a workflow that we no longer want to encourage. We want to solve [something else] instead because we think it will be better for customers in the long run. (Product Owner, Company C) (2)

5.2.2. Architecture and Quality are inherently intertemporal

Architectural decisions, in particular decisions explicitly focused on software quality, need to consider the future evolution of the system in its dual contexts of use and development. That temporal nature inevitably gives rise to intertemporal choices.

> ... We actually had one such example [recently], where we discussed whether we should exchange a part with our own service or incorporate it into another service. And the discussions there were... Creating a new service costs us more time. But then we can deploy it ourselves. (System developer, Scrum master, Company C) (3)

New features may have architectural implications that impact many parts of the software system. Knowledge about how the required changes will likely affect the system over time is important input for the intertemporal choice of whether, when, and how to implement the feature.

5.2.3. Platform choices are always intertemporal

Platform choices are inevitably intertemporal because they combine near-term concerns of a project with longer-term perspectives of future system maintenance, evolution and re-usability across projects and products. For example, when new technical solutions become available, the new possibilities they offer can create intertemporal choice situations for software companies. Existing investments may pull to the current platform, but a new platform beckons with benefits the current platform lacks.

> ... it would have been quicker to just continue with the old [platform] and continue developing and expanding it even further. But through the transition [to the new platform], we have partly gained the expertise to write mobile apps using the same techniques and have a more modular way of releasing our products. (Software developer, Scrum master, Company C) (4)

Software developers who are responsible for platform development face intertemporal choices when it comes to the direction of the platform.

> We have made changes to frameworks and the like that are mostly in the sense of "this will make it nicer and perhaps save time". But sometimes we choose not to do them and instead postpone. I believe it happens regularly. (Product owner, Software developer, Company C) (5)

5.2.4. Testing and QA involve shorter-term intertemporal trade-offs

Testing and quality assurance are continuous activities that centrally involve a consideration of risks. Time spent on testing can increase release times, and testing is often playing catch-up with development. Making testing and quality assurance activities more efficient is desirable, but the return on investment is often unclear.

Some technical designs are meant to mitigate against future problems. Risk analysis – formal or informal – can reveal potential events that have never occurred but are not impossible. These are *ambiguous* events, i.e. events for which it is very difficult to get reliable probability information. The potential future event is ambiguous while the action to address it in the present is much clearer, including an idea of the effort involved.

> Should we implement logging for something that has never happened, just in case it might happen? (Product Owner, Company C) (6)

Bug fixing can be viewed in isolation as a problem-solving activity that aims to find the cause for an undesired behaviour and correct it. However, in practice, it is sometimes not possible to focus only on that single problem-solving activity. Some aspect of the undesired behaviour may have to be addressed very urgently. This creates an intertemporal choice situation where at least two options must be considered: quickly deploying a fix that addresses the most pressing need, and taking the time to develop a longer-lasting change. Sometimes, both options can be taken.

> [We had a problem that occurred sporadically for a small number of customers.] ... Last Friday, I tried out a quick fix where I really only increased [a timeout] ... At the same time I was doing a bigger job to solve the bigger problem. That was actually a combination of a short-term fix to solve the problem for the customer, and at the same time [there's] a solution in progress to solve the bigger problem. (System Developer, Company C) (7)

5.3. Intertemporal choices are uncertain, ambiguous, temporal, and sociotechnical (RQ3)

Participants described similar situations in their work based on a recognition of salient characteristics, and in doing so, some reflected on the difference between the presented task and their practice. In the following we illustrate how long-established characteristics of intertemporal choice situations manifest in concrete examples in SE practice.

5.3.1. Intertemporal choices are often as ambiguous as they are uncertain

Across the range of situations where participants recognised intertemporal choices occurring, they emphasised a lack of information, particularly with regard to precise numeric data on effort and probabilities of success. This means that rather than dealing with uncertain probabilities as in the task example, the real-world situations our participants face in their work *lack probabilities* – i.e., the participants are faced with *ambiguity*. For instance, this is true for Quote 4. Additional clues in the interview beyond the quote show an explicit sense of ambiguity: there may be large benefits of the new platform, "but you never know". There is an indication of potential time savings that the new platform could provide in the long run, but also of a negative effect of learning in the present project. Either course of action comes with benefits *and* drawbacks – they are *mixed outcomes* [78] – and they are ambiguous.

> ... really this is ... pretty much the way it usually looks ... you have a feature here to implement. Then you may have something else, technical debt or something else that [you have to consider]. And then maybe there is even less information, we don't know how much we save on solving this technical debt or whatever it is. So [the scenario presented] is almost better than what we might have in most cases. It's a bit harder in reality to [make the decision] at least from our team's point of view. We have not dealt so much with numbers and such. (Junior system developer, Company C) (8)

Here too, the lack of numeric information supplying probabilities that could be fed into a weighted trade-off analysis is unmistakable: the participant's work situation does involve trade-offs, and they are intertemporal, but their values are not fixed estimates, ranges, or probabilities. Ambiguity is in the air.

5.3.2. Intertemporal choices extend beyond individual projects

Some intertemporal choices have outcomes that will occur during the present project. For others, the outcomes will only occur much later. It may be difficult to justify the cost or effort when the benefit cannot be reported for the present project. For example, the time and effort investment into building internal tools to maintain configuration or production data create intertemporal choices. Where is the best compromise between a rudimentary way to access data and a full-fledged internal product with provisions for access control and data quality? Shifting the time horizon will affect the outlook on this trade-off.

Investments in *skills development* is another intertemporal choice, and its outcomes are often ambiguous. One expectation is that training will lead to increased competence, in turn resulting in increased efficiency or quality. However, there are other desirable outcomes as well, such as increased morale and smoother teamwork, and intrinsic values to personal development. Thus, the decision to invest in training is not as clear-cut and instrumental as adding a feature or developing a tool. But in practice, these decisions sometimes overlap:

> We have a project right now, in fact, an internal tool for disseminating skills. I am probably a little more hesitant towards it than the team, but it is a huge morale boost for them, and it can work. ... What tips the scales for me is above all the fact that they want to build it. Had I made the choice myself in the beginning and not had any such emotional attachment to it from their side, I would probably have chosen not to do it, and put effort on other things. (Product owner, Software developer, Company C) (9)

5.3.3. Seemingly technical decisions often involve a range of social concerns

Decisions that look "technical" often involve concerns with varying timescales and require consultation with a range of stakeholders. For example, whether to integrate a third-party library with potential long-term benefits, or spend time on refactoring to reduce technical debt, is ultimately connected to a wide range of concerns in the software organisation. Decision-making processes in software design are at least as much about understanding the decision situation, developing arguments, creating options, and getting support for them, as it is about choosing a particular course of action:

> I think the first thing would be to talk to people who would be directly affected ... to see if one is thinking about [the idea] correctly. If it directly affects the product, then talk to the product [staff]; if it directly impacts the developers, then talk to the developers, and so on. ... Later, I think it would go to a conversation where everyone was affected, because if times are affected, the product manager, the product owner and the developers who are the ones that would directly affect the time would have to talk to each other. (Frontend Developer, Company A) (10)

Differences in *roles* influence decisions. The incentives, focus, and time horizons implied in a person's role may alter their perception of time.

> Usually consultants think differently. The developer has always in mind the improvement, because this is his job. The consultant would focus on being quick, immediate, something that can be shown, on something that can be presented to the client. ... The developer's job is essentially that, to save time, to make things more automated, because of the nature of his work. (Software Engineer, Company B) (11)

Across different roles, *personal characteristics* influence preferences during decision making. In the following example, the participant seeks a challenge and prefers a demanding deadline, making the task a personal competition.

> I ... strive to measure myself without methodologies that give me security, such as "you can do this in so-and-so many days because the methodology says so." I don't like that because I don't like to feel that I'm relaxing, and I feel that using methodology is like courting laziness in terms of time decisions. (Frontend/Backend Developer, Company A) (12)

Methods should provide structure and thus reduce uncertainty, and a possible locus of decisions to examine could be in the prescriptive structures of methods. For example, the Architectural Trade-Off Analysis Method ATAM involves the use of scenarios to explore possible outcomes [41, 14]. Still, the preceding example raises the question of what role methods-as-prescribed take on in different contexts. Companies differ in how they organise their practice based on method ideas. Decisions do not fall neatly into any particular method, but are rather socially situated in the organisation:

> ... each company is a different universe, it has a different culture, different methodologies. Even though many companies say they are agile, each [company] does [agile] differently, has different competencies, and different talent. (Product Manager, Company A) (13)

SE *methods* become highly customised in companies, sometimes to the extent that we cannot reliably tell what the role of a method is going to be in a particular organisation. Whether they originate from industry itself, from research, or a combination of both, methods are seldom understood or applied as originally intended, nor applied in the same way in each situation [29]. Software development can be seen as epistemic practice characterised by local adaptation and design of methods-in-use; a simultaneous unfolding of the system under development and the development practices [18]. This means that methods themselves are subject to interpretation and modification by those using them in practice. When considering decision-making in software design, methods should therefore be treated similarly to other cognitive resources, as part of the uncertain and ambiguous temporal field in which decisions are made.

5.4. Summary

Our interviewees identify intertemporal choices in many areas of their work. It appears that intertemporal choices surface throughout the practice of software systems development, but are more visible and pronounced in those areas that are explicitly concerned with longer-term evolution, such as architecture. In other words, intertemporal choices arise whenever teams are faced with opportunities to make decisions with lasting effects. The range given here should not be taken as complete, but circumscribed by the range of professional experience of our participants. The examples illustrate how intertemporal choices are related to and influenced by methods, personal characteristics, company differences, a wide range of concerns in the organisation, and different incentive structures depending on people's roles.

Table 1 maps the examples given above, and additional instances identified but not quoted, into general SE areas. It highlights that we can distinguish the emergence of intertemporal choices also in terms of their own temporality of occurrence – it makes a difference whether an intertemporal choice is identified early as an opportunity or emerges suddenly as

Area	An opportunity to plan ahead is identified. Should we ...	A choice situation arises. Should we ...
Architecture and Quality	Refactor or optimise for performance and scalability?	Reuse the existing micro-service? (3) How do we handle long-term implications of feature changes on our architecture?
Platform Strategy	Should we improve the platform? (5)	Migrate to a new platform? (4)
Testing	Log potential rare errors? (6)	Fix the bug quickly or develop a longer-term solution? (7)
Product Development	Focus on new features or on reducing technical debt? (8) How should we balance the competing priorities and feature requests knowing that their costs and benefits will shift over time? (1)	Prioritise the small feature that can gain us new customers or the larger more complex feature that our existing customers want? (2)
Beyond the project	Expand our training program? (9)	Upgrade our internal tools?
	Apply a method or work out the unique case? (12) Incorporate a new method to the company's way of working? (13) Involve a wide range of stakeholders to get their support? (10) Focus on quick delivery or spend time automating? (11)	

Table 1: Intertemporal choices arise in many areas of our participants' professional experience. The numbers refer to corresponding interview quotes.

a choice that has to be made. Proactively identified choices can be more carefully contemplated, but if the outcomes are in the distant future, they tend to be more ambiguous and harder to envision. At the other extreme, issues identified in hindsight as missed opportunities usually limit the available alternatives – when the critical bug is found, the critical bug has to be fixed.

6. Discussion

The results above demonstrate that temporal distance affects our participants' reasoning in very uneven ways (RQ1) and that intertemporal decision making is ubiquitous (RQ2). We also found that intertemporal choices are often uncertain *and* ambiguous and always socio-technical (RQ3). We now turn to discussing the implications of these findings for how intertemporal choices can be characterised and studied in SE, deepening the response for RQ3 by interpreting our findings through the lens of judgment and decision making.

6.1. A new lens for an old question

The intertemporal choices that our participants grapple with on a daily basis are not themselves novelties to SE theory. Many of these trade-off decisions are precisely what SE methods are designed to tackle. The longer-term implications of decisions made about product development, testing, architecture, or technical debt have constantly motivated the development of SE tools and methods. For example, software architecture research has long grappled with the question "how to make architectural design decisions sustainable" [91], i.e., how to make them last [85]; and technical debt management aims to identify the optimal balance between short- and long-term interests in software projects [2].

What does SE gain from exploring these questions through a psychological lens? Our empirical results show that the psychological view is a crucial frame for understanding the intertemporal nature of systems design. By allowing us to examine common SE decisions *as intertemporal*, the psychological view provides a new angle on common challenges in SE across multiple aspects of software development, including technical debt, architecture, project management, and sustainability. It provides insights into daily practice that methods miss to account for. It better explains what really happens when intertemporal trade-offs occur in practice, and how systematic methods interact with individual and team cognition. This is a crucial step towards effectively influencing the choices and outcomes and develop more sustainable software systems.

How software professionals *should* take these types of decisions has been exhaustively specified. For every question listed in Table 1, a sizeable choice of SE methods stands ready to support decision making. This concern with long-term effects of engineering decisions has been present since SE was founded as a discipline over 50 years ago and has never lost its central importance. Whether design decisions have genuinely become more sustainable during this period is unclear, but the range of available tools and techniques has increased considerably [91].

Recognising decisions as intertemporal from a cognitive and psychological perspective opens new opportunities for progress on this persistent challenge. By examining professional practice through this lens, we gain an inside view of the reality of making real-life intertemporal choices and an opportunity to look deeper into the interactions between methods and their use [18].

6.2. Rationalistic and naturalistic approaches to decision making research

Our results raise the question of how to understand decisions in SE practice. To illustrate how the lens of cognition and psychology can be applied to that question, let us consider Quote 6 as an example: *Should we implement logging for something that has never happened, just in case it might happen?* The interviewee, a product owner, recounts an exchange with a developer who suggested logging to be implemented to catch potential errors. The product owner asked probing questions about the plausibility of the error based on occurrence in the past and predictions about the future.

One way to understand this could be that decisions *should be* based on preconceived mathematical models. In the classic rationalist research paradigm dominating SE [89, 70], the situation would appear as a case of choice under probabilistic uncertainty. The paradigm's response to probabilistic uncertainty is to treat the situation as a quantitative trade-off problem and model its probabilities, costs, and benefits to recommend the optimal choice.

Similar ideas have been common in other fields. But extensive empirical studies since the 1960s have shown that rationalistic, mathematically-founded models of decision making are inconsistent with empirical observations. This debate is reflected within the history of SE research too [7]. Just like the discounted utility model, general models of expected utility that form the basis of most multi-criteria decision making research [42] are built not on studies of how people think, but on game theory [87] and the mathematical axioms of Bernoulli that prescribe how optimal choices *should be* made in risky situations such as gambling.

Decades of studies reveal that people do think in terms of rationalistic models for clearly circumscribed tasks, while processes such as the Recognition Primed Decisions model (RPD) [48] are used in many less circumscribed situations, for example to structure problems [55, 40]. Evidence for both modes of thinking has been found in SE [89]. The wildly diverging results in the task portion of our study, and the varied locations in which our practitioners recognised decisions, suggest that the basis for interpreting these decisions must be primarily a naturalistic one, with a normative rationalistic perspective being subordinate. No single model can be fitted to the data, nor can we say which responses are closest to being optimal.

It is thus unsurprising that many practitioners take a pass on rationalistic, normative methods:

- By assuming probability estimates, the rationalist paradigm does not effectively address the ambiguity that people experience. As a result, the only way to apply this paradigm's methods often is to pretend that it is possible to model and compute predictions. This sidesteps facing the actual issue of handling ambiguity. In the logging example, ambiguity is handled via deferral. Rather than trying to base a decision on information they lack, many practitioners recognise that they may never need it and choose a form of inaction *for now*.

- The rationalist paradigm provides no mechanism to distinguish between the immediate statement and the underlying framings and reframings that surface when groups discuss what to do. In our example, other interactions earlier and later must be understood before these framings become apparent.

- The paradigm also does not account for the nature of judgement and expertise as nuanced, reflective, situated forms of knowledge. For example, the person may have intuitive expertise manifesting as the hunch that with shifting context, this will become likely to happen for the first time. Far from originating in their gut, this hunch may surface because they have analogous experience with other systems that, when repurposed or reused across domains, had run into behavioural patterns previously thought 'impossible'. They may struggle to articulate this tacit knowledge precisely unless probed carefully [49, 16].

6.3. Limitations: Where next?

The restrictive design of our initial studies of intertemporal choice required participants to complete a particular sequence of questions with minimal researcher interaction. As we stated [26], "All we know is that people behave *as if* they would perform temporal discounting. We have not identified how or why this effect takes place, nor do we have a 'gold standard' of optimal decision making. There is no optimal decision to be made in the presented scenario, and there are many good reasons for discounting uncertain future outcomes." Because the study design did not examine participants' cognitive processes nor allowed them to interrogate the scenario and the provided information, the findings do not explain the reasoning underlying their responses. As noted in previous work [51, 68], knowledge of cognitive processes is important for understanding in depth how and why certain behaviours come about. Consequently, this article prepares the ground to couple quantitative observations of behaviours with a qualitative study of cognition to elucidate the underlying reasoning. Beyond the scope of this article, our current research further examines how our participants reasoned about intertemporal choices, which factors they considered, and how. As a new lens to an old question, this is a promising area of empirical SE research.

The present study places primary emphasis on the qualitative understanding of our participants' reasoning. Following advice from experts in qualitative research methodology regarding the dangers of quantifying inherently qualitative data [88, 17], and echoing similar decisions in previous work in SE [45], we do not make quantitative statements about the frequency of our qualitative findings in the general population of software professionals. We do, however, provide quantitative analysis of the questionnaire results, as prior studies.

7. A Framework for Studying Intertemporal Choice in SE

todo intro what this is; three parts: macrocognitive framework, research directions, guidelines

7.1. How should we characterise intertemporal SE choices?

We are now ready to use concepts from JDM research to structure future analyses of intertemporal choices. To characterise intertemporal choices in SE, account for:

1. The **context** in which the decision occurs, understood for now in the widest sense as anything that influences the decision. Typically,

the context concerns the social and historical environment in which decision makers act.

2. **Commitment:** Decisions are commitments to actions, but which actions are available to commit to? This is not always a selection out of explicitly enumerated options – often, some or all of the actions are generated by the decision makers in the course of decision making [48]. They may appear as explicit, well-defined “options” to choose between. But more often than not, there are myriad ways in which to proceed, and an option is something that can be defined only in hindsight as the action to which the decision-maker in fact committed or could have committed to but did not. Understanding this for each situation is a key to understanding real-world decision making behaviours.

3. **Uncertainty** covers uncertain properties of the options and possible outcomes *as well as* their ambiguity. Uncertainty, or *risk*, refers to the objective probability of potential outcomes. *Ambiguity*, on the other hand, means that only vague information about the probabilities is available [21]. Uncertainty about uncertainty complicates how people think about possible outcomes when they decide [12]. It may be uncertain whether something will happen or not; who it will happen to; and what it will mean at the time if it happens. The distinction between the two matters because they are different and must be handled differently.

4. The **temporal dimension** separates possible outcomes across time and can involve multiple timescales that need to be considered simultaneously. Time always introduces uncertainty about the outcomes and often also ambiguity regarding both the options and the outcomes.

5. The **situated cognitive processes** of individual decision-makers possibly acting as a group. Intertemporal choice raises difficult questions about cognition that are not adequately understood yet. For example, people differ in their *ambiguity attitude*: some are drawn to ambiguous options while others avoid them. Several studies indicate that attitudes towards ambiguity depend on the likelihood of the uncertain events, the domain of the outcome, and the source that generates the uncertainty [83]. This means that decisions cannot be understood only through the temporal separation of the outcomes. It is crucial to understand how the outcome uncertainty is perceived by decision-makers.

Given these characteristics, we can now give an account of how the intertemporal choice situation in the logging example can be understood.

1. *Context:* This team-based agile company uses projects to develop new features for their products, which are delivered as Software as a Service. The time horizon of team responsibility extends beyond projects, with longer-term relations to customers (SMEs in a range of domains). Slowly shifting customer segments can cause domain contexts and user behaviour to evolve.

2. *Commitment*: The initial question is "To log or not to log", but presumably, there will be more nuanced options available to generate ("Let's do a minimum amount of logging?").

3. *Uncertainty* is in the air. While the anticipated incident to log has never happened before, someone has brought it up because they believe it might. With shifting domain contexts, behaviour that is currently very improbable may become more likely, but hard to estimate – in a word, ambiguous. In fact, the quote itself is ambiguous. Did you read it as suggesting that it *should* be done? Then imagine it starting as "Should we *really* implement logging...?" – this may better capture the nuance in the ambiguous Swedish original.

4. *Temporality:* The time dimension is open-ended, extending beyond the current sprint and the completion of the current project. Outcomes are in an ambiguous future. The quote also harks back to the past in noting that nothing bad has happened yet.

5. *Situated cognitive process:* The interviewee's story suggests a value of 'being prepared' and raises the explicit trade-off: 'how should we allocate our time now?'. The discussed option is already a compromise: We do not invest time to prevent the unlikely outcome to happen, but we may want to invest just enough time to detect it. In the conversation surrounding the quote, the product owner emphasised the agile value of avoiding unnecessary work. They decided not to implement logging 'just in case it might happen'. The different roles involved in discussing this choice brought distinct framings, interests and motivations to the group decision. Different kinds of authority were also at play: management, by virtue of allocated responsibility; a seasoned developer, by virtue of their expertise as recognised via their reputation.

By characterising this decision via its context, the commitment made, the uncertainty surrounding it, the temporality, and the cognitive facets of the decision, we gain a more accurate understanding of real-world practice. While mundane, our example shows how differently just a single, simple example can be understood. When situations and questions larger and smaller appear on a daily basis, we can see how software professionals are constantly faced with the challenge of overcoming the confusion of time.

We can now begin to understand why a normative method of criteria-based choice does not suffice to address the nature of intertemporal choices. By treating the cognitive process as machinery, the rationalist model prematurely abstracts the nuances of the substance that makes up what happens. This simply does not address the real difficulties that practitioners face in a situation where they attempt to exercise careful judgement. By appreciating it as a human and social phenomenon taking place in a specific context (1), we gain the perspective to develop more appropriate ways of supporting good choices. We need the specific context to make sense of the situation and understand how intertemporal choices arise. Individual cognitive processes (5) act together on the small-group level to handle temporality (4) and uncertainty (3) and reach a commitment (2). The cognitive and social aspects of practising individuals and teams, the specific project factors, the methods and tools used by the teams, the organisational context, and the larger context in which the organisation operates all come together to influence decision-making.

7.2. Research Directions

What can we do with this new understanding? TODO finalize – brainstorm: - bypass misleading, rationalist accounts that produce appealing but flawed explanations and simple but ineffective interventions - instead, identify strengths of decision makers, identify strategies of success, enable newcomers to learn from experienced decision makers, design effective interventions that allow teams to be more intentional about their choices...

On an applied practical level, this makes an immediate difference in how we understand what happens in practice. For example, a decision making researcher in SE who encounters the logging example above in collaborative research with a software company could use this and similar situations to help the team analyze and reflect how their decisions take place. They can help the team - to understand and make visible the sources of uncertainty and ambiguity - to identify and map the temporal scales of relevance - to make intentional choices about the temporal horizon and scope - to evaluate the context of decision making and identify which factors contribute to short sighted decisions that can be removed, and which factors contribute to wise judgments that could be amplified - in other words, they can support the team in gaining an understanding of what actually happens, and to identify and potentially redesign how they make their intertemporal choices. The outcome may well be a sort of method, but more likely, it will be a combination of three things: - a heightened appreciation and awareness of how decision making practice is influenced by situational and contextual factors - a set of techniques to address factors that are understood to distort decision making - processes for reflection, analysis, and knowledge sharing in the team that support team members in learning from each other.

On the theoretical level, it is clear now that understanding decisions across time in SE requires a much more comprehensive research roadmap than the one implied by normative rationalistic models and methods. We argue here that this roadmap must be firmly grounded in reference disciplines such as psychology, ask questions across the spectrum of the practice, point to suitable methods and designs for obtaining answers, and provide a conceptual framework to build theory and actionable interventions. Some starting research questions are given here.

The goal should be to promote sustainable software design decisions, whether we seek to avoid locking ourselves into inflexible technical designs, setting ourselves up for large future costs, or harming our societies or the disadvantaged. Some situations are more conducive to produce sustainable decisions, but what are they like and how do they work?

By using interview techniques from CTA, SE researchers can identify critical incidents of intertemporal choices in SE practice and investigate which factors influenced the decision and how the practitioners make their choices. That is the first step to understanding what changes can be most effective to increase the sustainability of decisions. A more effort-intensive but very promising approach would be an ethnographic study of industry practice sensitized to naturalistic decision making concepts and methods, building on the work of decision making researchers [47] and SE ethnographers [77]. Staying with the action with the help of these organizing principles should allow researchers to take the field's understanding of its practice to new levels.

Many starting points for research questions wait in the baseline we have presented. For example, intertemporal choice behaviour varies wildly across different studies and participants [31]. Why did our participants with a broader range of work experience discount future choices less than others [26]? Broad experience may bring with it the ability to make more detailed mental simulations or to use richer imagination to consider the implications of different options. One aspect of the situation is thus who is there and what experience they bring with them.

Real-life choices in software systems design are impacted not only by individual-level factors, but also by the context in which decisions are made and how decisions are framed. Design decisions are complex, iterative, and usually ambiguous. Other situational characteristics that can influence the sustainability of design decisions include the time horizon of projects, staff turnover, reward and incentive systems, distribution of responsibility, and contracts. What are relevant patterns of situational characteristics? Which situational anti-patterns foster unsustainable decisions? An empirically grounded, robust collection of situational patterns and anti-patterns can provide highly impactful starting points for translating insights into practical improvements and pedagogical materials.

7.3. Research Guidelines: How should we study intertemporal SE choices?

The problem areas discussed above give directions and motivations for research on intertemporal choice in SE. The following guidelines are a minimal set to consider when designing research studies and in evaluating their outcomes, including in peer-review. The first two address scoping and clarity of what is being studied; the next three address clarity in conceptual design on the axes of scope, control, and intervention; the final two address methodology. Together, they expand our response to RQ3.

The Decision: Clearly describe each element of intertemporal choice (commitment, uncertainty, temporality, situated cognition, context) to position each decision in its situation and social context. The distinction between uncertainty and ambiguity is crucial [21, 12, 83]. Research designs should be flexible enough to recognise that decisions happen not only where prescriptive methods place them, but at any point where those involved can make different commitments. In some cases, commitment(s) only become visible in hindsight. Follow the lead of practitioners when they make decisions differently from how, where and when the methods prescribe them.

Discounting: Studies must follow the state of the art in JDM research when it comes to describing and evaluating intertemporal choices. This requires caution in the face of normative models of temporal discounting, careful selection of measurement methods (such as the use of AUC as a theory-free measure of time preference [26]), and it means we must examine the interactions between perception, time preference, and the *psychological distance* [84] between decision-makers and those who are influenced.

Scope: Position each study carefully in the systemic context it examines to explicitly draw the boundaries of concern: what is observed, what is assumed, what is cut out from attention, and why?

Control: Carefully substantiate which contextual elements and relationships are controlled and which are not, and evaluate what degree of freedom this introduces and how.

Intervention: Clearly define the element of intervention, if any, and if possible, include control groups with no intervention. Carefully consider established methods for observational and interventional studies to increase validity.

Method: Clearly specify and justify the research method. The topic of intertemporal choice has been investigated for almost two centuries [31], and fields such as JDM have accumulated vast methodological experience that should be reused and repurposed before developing SE-specific research methods. That said, the nature of decisions and situations in systems design *is* peculiar. For example, the nature of professional expertise distinguishes our participants from many consumer-focused studies in JDM, and the nature of temporality is baked into the domain. So at some point, with sufficient stable ground under our feet, we will be in a position to build new methodologies more attuned to socio-technical design work.

Replication: Document and release study designs, protocols, and data to enable replication, making use of open data repositories (examples exist, e.g., [25]). The overall emphasis should be on the *recoverability* of research design choices, since direct replication is not suitable for all studies [58, 33]. Where applicable, invite others to replicate the work, both in direct collaboration but also as independent work; be prepared to support the replicators with clarifications, details, and data if needed. Carefully consider guidelines on replication [13].

8. Conclusions

As software pervades society, SE is now faced with challenges that go much beyond what most methods used today are prepared to address. A software system can impact people beyond the customer, users, and other stakeholders that current practices identify. Once we start looking, intertemporal choices can be found everywhere in systems design. Their temporal nature provides important clues to how systems design could become more sustainable. By appreciating intertemporal choice from a JDM perspective, we gain new opportunities for research and innovation. Intertemporal choice brings a new lens to a central question of SE.

In intertemporal choice, the *when* of the outcome intersects with the *who*. The decision-makers of the present may not be the ones who bear the consequences of their designs in the future. Decision-makers can more readily identify stakeholders close to themselves and cater to their needs than those who are distant. Stakeholders may be both internal to the software organisation, such as the developers who must deal with past design choices, and external, yet unknown groups of people whose lives are affected. As consequences shift further into the future, knowing who will be affected, and how, becomes increasingly difficult. But even when those more distant stakeholders *could* be considered, they often are not.

Situations in which intertemporal choices are made are often as ambiguous as they are uncertain. We have shown that some software professionals exhibit temporal discounting, but others do not. Why and how do their reasons differ? What can we learn to make future decisions more sustainable? The range of behaviours suggests that many different factors play into intertemporal choices. To characterise these decisions, and other similar situations, we introduced a set of five characteristics and showed how such a characterisation can result in viewpoints different from those of prevailing rationalistic approaches. Our example shows how to unpack the intertemporal characteristics of concrete situations that arise in everyday software projects and hunt for more situations to examine. The protocol we have presented yields much richer data than we can cover in this paper. Future analyses should move beyond the questions and analyses discussed in the paper.

Promising opportunities for studies await. We suggested a direction towards SE interventions that aim for more sustainable decisions when a temporal aspect is involved, and present her a foundation for future studies. Intertemporal choice offers a new angle on a problem as old as SE. It is now time to forge a perspective where consequences at different points in the future can be taken into account for a much wider range of stakeholders than SE methods have acknowledged before. We offer our previous work with openly published data sets [6, 26], and the materials of the present study, as potential starting points for inspiration.

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