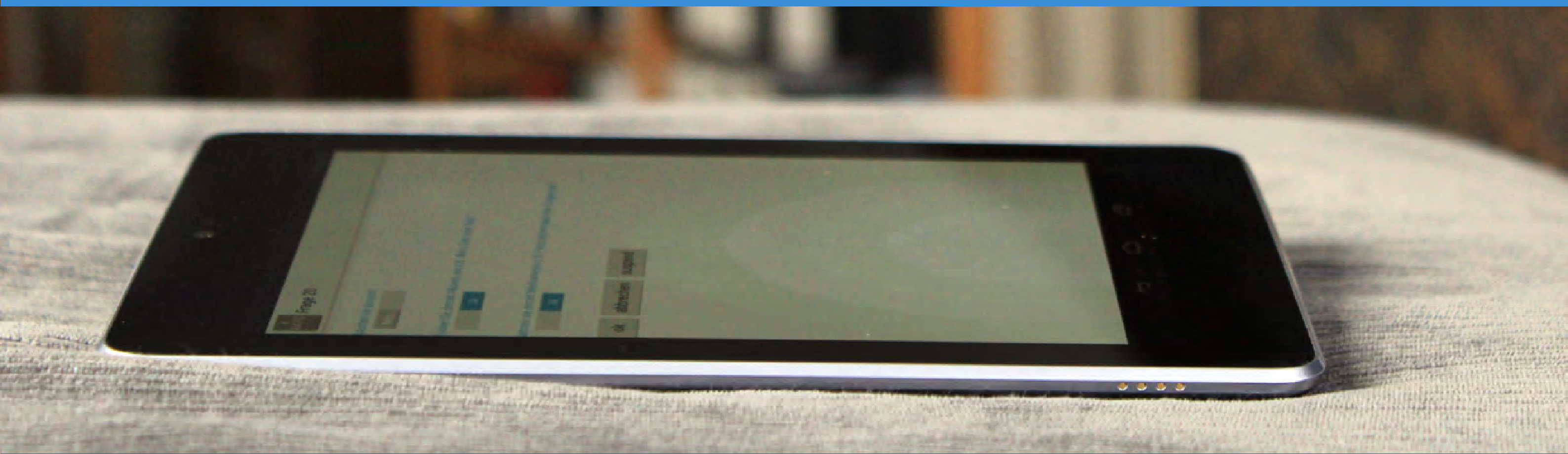
A Model-Driven Framework for Enabling Flexible and Robust Mobile Data Collection Applications

Johannes Schobel



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"Begin at the beginning and go on till you come to the end: then stop."

(Lewis Carroll, Alice in Wonderland)

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Vorwort

Die hier vorliegende Dissertation ist im Rahmen meiner beruflichen Tätigkeit als Doktorand und wissenschaftlicher Mitarbeiter am *Institut für Datenbanken und Informationssysteme* der Universität Ulm entstanden. In dieser Zeit habe ich viele Personen kennengelernt, ohne deren Unterstützung diese Arbeit in diesem Umfang und dieser Form nicht denkbar gewesen wäre – dafür möchte ich mich bedanken.

Zuerst möchte ich Herrn Prof. Dr. Manfred Reichert für die tatkräftige Unterstützung während meiner Promotionszeit und das freundliche Aufnehmen im Institut – schon damals während meiner Zeit als Student – danken. Noch mehr jedoch möchte ich mich für deine kollegiale Art und dein Vertrauen in den letzten 6 Jahren mir gegenüber bedanken. Darüber hinaus möchte ich Herrn Dr. Winfried Schlee für die vielen positiven Gespräche und zahllosen Ideen in diesem Themenumfeld danken.

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Weiter möchte ich “meinen” Studenten danken, die mich in zahlreichen Projekt- und Abschlussarbeiten tatkräftig unterstützt haben. Besonderer Dank geht dabei an Steffen Scherle, Juri Schulte, Karoline Blendinger, Arnim Schindler, Thomas Miholic, Fabian Maier, Wolfgang Wipp, Robin Martin, Philipp Butz, Jens Winkler, Fabian Widmann, Dominic Gebhardt und Lena Arndt.

Zuletzt möchte ich mich bei meiner Partnerin und meiner Familie für die Unterstützung, Geduld und den Rückhalt bedanken; Ihr wisst, wie dankbar ich euch bin.

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Abstract

In the light of the ubiquitous digital transformation, smart mobile technology has become a salient factor for enabling large-scale data collection scenarios. Structured instruments (e.g., questionnaires) are frequently used to collect data in various application domains, like healthcare, psychology, and social sciences. In current practice, instruments are usually distributed and filled out in a paper-based fashion (e.g., *paper-and-pencil questionnaires*). The widespread use of smart mobile devices, like smartphones or tablets, offers promising perspectives for the controlled collection of accurate data in high quality. The design, implementation and deployment of mobile data collection applications, however, is a challenging endeavor. First, various mobile operating systems need to be properly supported, taking their short release cycles into account. Second, domain-specific peculiarities need to be flexibly aligned with mobile application development. Third, domain-specific usability guidelines need to be obeyed. Altogether, these challenges turn both programming and maintaining of mobile data collection applications into a costly, time-consuming, and error-prone endeavor.

The Ph. D. thesis at hand presents an advanced framework that shall enable domain experts to transform paper-based instruments to mobile data collection applications. The latter, in turn, can then be deployed to and executed on heterogeneous smart mobile devices. In particular, the framework shall empower domain experts (i.e., *end-users*) to flexibly design and create robust mobile data collection applications on their own; i.e., without need to involve IT experts or mobile application developers. As major benefit, the framework enables the development of sophisticated mobile data collection applications by orders of magnitude faster compared to current approaches, and relieves domain experts from manual tasks like, for example, digitizing and analyzing the collected data.

Zusammenfassung

Getrieben durch die fortschreitende digitale Transformation nehmen mobile Technologien einen immer größeren Stellenwert für das Erfassen großer Datenmengen ein. Insbesondere in der Medizin, der Psychologie und den Sozialwissenschaften werden häufig strukturierte Instrumente (beispielsweise Fragebögen) eingesetzt, um Daten in unterschiedlichen Szenarien und Studien mobil zu erfassen. Diese werden allerdings, trotz bekannter Nachteile immer noch größtenteils, in papierbasierter Form durchgeführt. Die flächendeckende Verbreitung mobiler Endgeräte (beispielsweise Smartphones oder Tablets) ermöglicht visionäre Ansätze zur kontrollierten Erhebung großer Datenmengen in hoher Qualität. Die Konzeption, Entwicklung und Verteilung mobiler Anwendungen zur kontrollierten Datenerhebung ist allerdings aus mehreren Gründen herausfordernd. Erstens müssen für eine breite Nutzbarkeit unterschiedliche mobile Betriebssysteme (beispielsweise Android und iOS) adäquat unterstützt werden. Eine besondere Schwierigkeit bilden die relativ kurzen Entwicklungszyklen dieser Plattformen. Zweitens müssen Besonderheiten der jeweiligen Anwendungsdomäne berücksichtigt und mit dem Entwicklungsprozess für mobile Anwendungen in Einklang gebracht werden. Drittens sollten domänenspezifische Anforderungen für Benutzeroberflächen und -schnittstellen berücksichtigt werden. Insgesamt ist die Entwicklung und Wartung mobiler Anwendungen zur kontrollierten Datenerhebung daher kostspielig, aufwändig und fehleranfällig.

Die vorliegende Dissertation stellt ein umfassendes Rahmenwerk vor, welches es ermöglicht, papierbasierte Fragebögen in mobile Anwendungen zur digitalen Datenerhebung zu transformieren. Die resultierenden Anwendungen können dann auf unterschiedlichen mobilen Betriebssystemen und Gerätetypen ausgeführt werden. Das entwickelte Rahmenwerk soll insbesondere Fachanwender aus verschiedenen Domänen (beispielsweise Medizin oder Psychologie) in die Lage versetzen, solche mobilen Anwendungen eigenständig zu entwickeln und zu nutzen, d.h. ohne Einbinden von IT-Experten oder Programmierer. Das Rahmenwerk erlaubt es einerseits, komplexe Anwendungen zur Datenerhebung wesentlich schneller als bisher zu entwickeln, andererseits werden manuelle Tätigkeiten, wie das Übertragen der erhobenen Daten in digitale Formate und deren Analyse, erheblich vereinfacht.

List of Publications

This cumulative dissertation is a consolidated report of the research results obtained during the author's Ph. D. project. The detailed results have been published in the following refereed papers:

SPPSSR18 J. Schobel, R. Pryss, T. Probst, W. Schlee, M. Schickler, and M. Reichert. Learnability of a Configurator Empowering End Users to Create Mobile Data Collection Instruments: Usability Study. *JMIR mHealth and uHealth*, 6(6):e148, 2018

SPSR17a J. Schobel, R. Pryss, M. Schickler, and M. Reichert. Towards Patterns for Defining and Changing Data Collection Instruments in Mobile Healthcare Scenarios. In *30th IEEE Int'l Symp on Computer-Based Medical Systems (CBMS)*, June 2017

SPSPGSR17 J. Schobel, R. Pryss, W. Schlee, T. Probst, D. Gebhardt, M. Schickler, and M. Reichert. Development of Mobile Data Collection Applications by Domain Experts: Experimental Results from a Usability Study. In *29th Int'l Conf on Advanced Information Systems Engineering (CAiSE)*, number 10253 in LNCS, pages 60–75. Springer, June 2017

SPSR16 J. Schobel, R. Pryss, M. Schickler, and M. Reichert. A Lightweight Process Engine for Enabling Advanced Mobile Applications. In *24th Int'l Conf on Cooperative Information Systems (CoopIS)*, number 10033 in LNCS, pages 552–569. Springer, October 2016

SPSR16a J. Schobel, R. Pryss, M. Schickler, and M. Reichert. A Configurator Component for End-User Defined Mobile Data Collection Processes. In *Demo Track of the 14th Int'l Conf on Service Oriented Computing (ICSOC)*, October 2016

SPSR16b J. Schobel, R. Pryss, M. Schickler, and M. Reichert. Towards Flexible Mobile Data Collection in Healthcare. In *29th IEEE Int'l Symp on Computer-Based Medical Systems (CBMS)*, pages 181–182, June 2016

SPWSR16 J. Schobel, R. Pryss, W. Wipp, M. Schickler, and M. Reichert. A Mobile Service Engine Enabling Complex Data Collection Applications. In *14th Int'l Conf on Service Oriented Computing (ICSOC)*, number 9936 in LNCS, pages 626–633, October 2016

SPSRER16 J. Schobel, R. Pryss, M. Schickler, M. Ruf-Leuschner, T. Elbert, and M. Reichert. End-User Programming of Mobile Services: Empowering Domain Experts to Implement Mobile Data Collection Applications. In *5th IEEE Int'l Conf on Mobile Services (MS)*, pages 1–8. IEEE Computer Society Press, May 2016

SPR15 J. Schobel, R. Pryss, and M. Reichert. Using Smart Mobile Devices for Collecting Structured Data in Clinical Trials: Results From a Large-Scale Case Study. In *28th IEEE Int'l Symp on Computer-Based Medical Systems (CBMS)*, pages 13–18. IEEE Computer Society Press, June 2015

SSPR15 J. Schobel, M. Schickler, R. Pryss, and M. Reichert. Process-Driven Data Collection with Smart Mobile Devices. In *10th Int'l Conf on Web Information Systems and Technologies (Revised Selected Papers)*, number 226 in LNBIP, pages 347–362. Springer, 2015

Additionally, parts of this thesis have been published in the following publications.

- J. Schobel, R. Pryss, M. Schickler, and M. Reichert. Process-Driven Mobile Data Collection (Extended Abstract). In *8th Int'l Workshop on Enterprise Modeling and Information Systems Architectures (EMISA)*, June 2017
- M. Schickler, M. Reichert, R. Pryss, J. Schobel, W. Schlee, and B. Langguth. *Entwicklung mobiler Apps: Konzepte, Anwendungsbausteine und Werkzeuge im Business und E-Health.* eXamen.press. Springer Vieweg, October 2015
- J. Schobel, M. Schickler, R. Pryss, M. Reichert, and T. Elbert. A Domain-Specific Framework for Collecting Data in Trials with Smart Mobile Devices. In *XIV Congress of European Society for Traumatic Stress Studies (ESTSS) Conf*, June 2015
- D. Isele, M. Ruf-Leuschner, R. Pryss, M. Schauer, M. Reichert, J. Schobel, A. Schindler, and T. Elbert. Detecting Adverse Childhood Experiences with a Little Help from Tablet Computers. In *XIII Congress of European Society of Traumatic Stress Studies (ESTSS) Conf*, pages 69–70, June 2013
- M. Ruf-Leuschner, R. Pryss, M. Liebrecht, J. Schobel, A. Spyridou, M. Reichert, and M. Schauer. Preventing Further Trauma: KINDEX Mum Screen - Assessing and Reacting Towards Psychosocial Risk Factors in Pregnant Women with the Help

of Smartphone Technologies. In *XIII Congress of European Society of Traumatic Stress Studies (ESTSS) Conf*, pages 70–70, June 2013

- J. Schobel, M. Ruf-Leuschner, R. Pryss, M. Reichert, M. Schickler, M. Schauer, R. Weierstall, D. Isele, C. Nandi, and T. Elbert. A Generic Questionnaire Framework Supporting Psychological Studies with Smartphone Technologies. In *XIII Congress of European Society of Traumatic Stress Studies (ESTSS) Conf*, pages 69–69, June 2013
- J. Schobel, M. Schickler, R. Pryss, H. Nienhaus, and M. Reichert. Using Vital Sensors in Mobile Healthcare Business Applications: Challenges, Examples, Lessons Learned. In *9th Int'l Conf on Web Information Systems and Technologies (WEBIST), Special Session on Business Apps*, pages 509–518, May 2013

Contents

Part I

Problem Description and Backgrounds

1

Introduction

In a variety of application domains, the controlled collection of large datasets with a high quality and validity is of paramount importance. Domains like healthcare, psychology and social sciences, for example, rely on well designed and established *instruments* (e.g., self-report questionnaires) to collect data in large-scale scenarios (e.g., clinical or psychological trials [20]). In current practice, datasets are predominantly collected with *paper-based questionnaires*, which are disadvantageous in several respects. Before processing and analyzing the collected data, for example, the latter has to be transferred to digital spreadsheets – a process that is time-consuming as well as error-prone, especially in the context of large-scale trials.

According to [63], approximately $50 - 60\%$ of the costs related to the collection, transfer and processing of data could be saved when relying on digital instruments instead of paper-based ones. This especially applies to long-running data collection procedures. Studies have proven that the use of digital instruments does not affect psychometric properties of subjects [14], but rather contributes to more complete datasets compared to the ones collected in a paper-based way [52]. This, in turn, significantly increases data quality [62], while decreasing the time required to collect the data [43]. Finally, studies have revealed that the use of smart mobile devices for collecting data might pave the way for new findings [19]. Moreover, digitally collected data may be enriched with contextual information (e.g., time and location of an interview [70]), vital parameters collected with sensors (e.g., pulse measurement during an interview [49]), or environmental data (e.g., weather [102] or noise). Altogether, digital data collection is increasingly demanded by domain experts in a multitude of application domains.

1.1 Problem Statement

Although there exists research works demonstrating the applicability of smart mobile devices in data collection scenarios [24, 64, 76], current approaches are rarely used in large-scale scenarios (e.g., clinical or psychological trials). Note that in such scenarios thousands instances of an instrument need to be processed. Other works investigated the use of smart mobile technologies in limited scenarios [7, 13, 55].

Regarding the development process of mobile data collection applications several challenges need to be tackled.

Mobile operating systems: The application to be developed may have to be provided for a broader audience. Amongst others, the application needs to be provided for a variety of mobile operating systems (e.g., Android vs. iOS). However, each mobile operating system relies on specific programming languages (e.g., `Java` or `Kotlin` for Android and `ObjectiveC` or `Swift` for iOS) and proposes specific user interface guidelines, adding complexity the to development process of the mobile application. *Cross-platform development* frameworks [31] may be used to bridge this gap and to deploy the developed application to various platforms. Corresponding approaches, however, are usually limited to features provided across all platforms.

Lifecycle and release management: Developers need to cope with short release cycles of mobile platforms, resulting in costly and time-consuming adaptations to be able to continuously support new releases. In this regard, multiple versions of a mobile application may co-exist at the same time, which increases complexity significantly.

Sensors: Internal and external sensors have to be integrated properly in order to meet advanced requirements set out by domain experts.

Practical use: Challenges related to the deployment and practical use of mobile application may emerge (e.g., security concerns in a hospital environments) [18].

Assist users: Transferring complex navigation logic of a paper-based instrument to its digital counterpart to guide (untrained) users during the *process of data collection* (e.g., to skip questions based on already given answers or to validate data) causes considerable communication efforts between domain experts and application developers [37].

Fig. 1.1 illustrates these challenges. To the best of the authors knowledge, no generic approach exists that supports the transformation of paper-based instruments to smart mobile applications in the context of data collection scenarios.

In a pre-study of this Ph. D. thesis, various mobile data collection applications were realized (cf. Table 1.1). As these mobile applications were *specifically tailored* to their application scenario, the aforementioned drawbacks re-emerged for each scenario. Domain

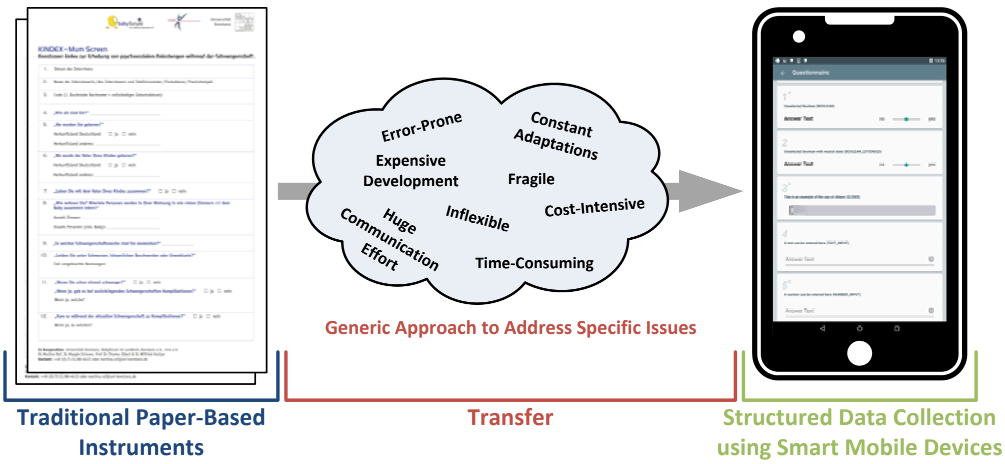


Figure 1.1: Contribution of the Thesis

experts working with these mobile applications, however, craved for more advanced features, e.g., to enable audio recordings during interviews or to provide on-demand evaluations based on pre-specified rules. Maintaining such complex applications for various mobile platforms, in multiple versions and languages, and over a long period of time constitutes a challenging endeavor.

Data Collection Scenario	Country	CN	Duration (Years)	Application Versions	Collected Datasets
Study on Tinnitus Research [68]	World-Wide	○	5 +	5	≥ 45,000
Risk Factors during Pregnancy [84]	Germany	○	5 +	5	≥ 1,500
Risk Factors after Pregnancy	Germany	○	2 +	1	≥ 500
PTSD in War Regions [108]	Burundi	●	4	5	≥ 2,200
PTSD in War Regions [129]	Uganda	○	1	1	≥ 200
Adverse Childhood Experiences [35]	Germany	●	2	3	≥ 150
Learning Deficits among Medical Students	Germany	●	1	3	≥ 200
Supporting Parents after Accidents of Children	EU	○	3 +	6	≥ 5,000
Overall				29	≥ 54,750

CN = Complex Navigation; PTSD = Post-Traumatic Stress Disorder

Table 1.1: Mobile Data Collection Applications Developed

In order to cope with these drawbacks as well as emerging requirements from various application domains, a generic approach is required. On one hand, such an approach, needs to cope with the process of developing mobile data collection applications in general, with the goal to reduce the time and costs required for realizing a data collection scenario. On the other, the approach shall reduce the communication efforts for application developers and domain experts. Most importantly, the approach shall empower domain experts to develop specific mobile data collection applications serving their needs.

1.2 Research Contribution

When writing this thesis, only little research was available targeting at the support of domain experts in developing domain-specific data collection applications, which then can be used in large-scale scenarios (e.g., clinical trials). In consequence, this thesis aims at developing fundamental concepts, techniques and prototypes for developing mobile data collection applications. The research contributions are summarized in the following:

1. *Requirements* from a variety of application scenarios are elicited and collected based on structured interviews with experts from the respective domains. Furthermore, additional insights are gathered when realizing several mobile data collection applications that shall support domain experts in their daily data collection procedures.

2. The thesis proposes a *lifecycle* that covers different phases of data collection scenarios in general. These phases, in turn, as well as their characteristics are observed for several mobile data collection applications. Further, the lifecycle may act as a blueprint for collecting data in large-scale scenarios in general.

3. A well-formed *mapping* is described based on which paper-based instruments can be transformed to digital data collection instruments that can then be deployed to and executed on smart mobile devices. This mapping, in turn, is based on the idea of describing instruments in a process-centric way.

4. A *domain-specific modeling language* is proposed that enables domain experts to develop data collection instruments themselves. Moreover, the proposed (graphical) modeling notation builds upon BPMN 2.0, but omits language elements not needed in the given application context. Finally, this language shall simplify the modeling process in general, by not overloading domain experts with unnecessary information.

5. A conceptual *architecture* is presented, which enables domain experts to develop specific data collection applications: The components of this architecture are related to the lifecycle, and aim at properly supporting domain experts in collecting data in large-scale scenarios. Finally, it is illustrated how process management technology may serve as a fundamental pillar of the architecture, allowing for a high degree of flexibility.

6. The conceptual architecture is implemented in the *QuestionSys framework*. In this context, proof-of-concept prototypes are developed for all major components to demonstrate the applicability of the proposed approach.

7. A set of common *patterns* that may be used to create and adapt data collection instruments are discovered from real-world data collection scenarios. These patterns are implemented by an advanced configurator component. Their semantics, however, is independent from a specific modeling language, i.e., the patterns may be applied in the context of other configurators as well.

8. The configurator as well as its underlying graphical modeling language are validated in various *usability studies* to demonstrate its applicability. In this context, recruited participants from various fields worked with the configurator to develop specific mobile data collection instruments.

Altogether, the developed framework aims at supporting domain experts to develop domain-specific mobile data collection applications on their own. A comprehensive set of prototype applications have been developed proving the practical feasibility of the QuestionSys approach and overall applicability.

1.3 Outline

This cumulative Ph. D. thesis is structured into four parts:

Part I motivates the need for utilizing smart mobile devices for collecting data in large-scale scenarios (cf. Chapter 1). Furthermore, background information is presented in Chapter 2, whereas Chapter 3 discusses design approaches for realizing mobile data collection applications.

Part II presents the developed QuestionSys framework. The publications SPSR16 [112], SPSR16a [113], SPWSR16 [115], and SPSRER16 [114] report on major contributions achieved in this context. Additional insights are provided in [107, 109, 111, 116]. Chapter 4 presents the overall concept of *modeling* data collection instruments. Further, it describes how *(Business) Process Management* technologies can be used to drive the developed approach. Chapter 5 considers core components of the QuestionSys framework, e.g., the configurator and mobile data collection applications. In Chapter 6, key aspects of the framework are summarized, whereas Chapter 7 discusses related approaches from research and industry.

Part III validates the QuestionSys framework and its components. The publications SPSPGSR17 [118] and SPPSSR18 [119] discuss major findings gathered in this context. Chapter 8 presents *usability studies*. More specifically, the complex study design used to evaluate the developed configurator is sketched, and major findings of the studies are presented. Chapter 9 reports on related work and compares the approaches with the conducted studies.

Part IV concludes the thesis. Chapter 10 highlights major scientific contributions and provides an outlook on future work.

2 Fundamentals

This chapter introduces fundamental concepts needed for the understanding of this thesis.

2.1 Instruments

Psychological Instrument

The term *psychological instrument* origins from the German *Psychologischer Apparat* [26], as it originally referred to machines for properly executing scientific experiments. Nowadays, psychology utilizes *tests* performed in standardized situations and environments to draw conclusions on specific human behavior. Corresponding tests can be subdivided into questionnaires, rating scales, and standardized interviews [26]. The author of [26] defines psychological instruments as *"an association of some material object and a process-generating rule, or a somehow materialized procedural rule, which for psychological research, teaching or practice, represents or adapts a part of the rational knowledge of a particular society at a particular time, that knowledge possibly but not necessarily being psychological"*. This thesis denotes *questionnaires* as *instruments* in the following.

Instrument Structure

During this Ph. D. thesis, a multitude of instruments from various domains (e.g., healthcare, psychology, and logistics) were analyzed. More precisely, interviews with experts from various domains were conducted to gain insights into the use of instruments in practice as well as to reveal recurring *structural elements*. In this context, a set of basic elements frequently used across a variety of instruments were discovered (cf. Table 2.1). These elements include, for example, *descriptive elements*, like headlines or texts

Structuring Elements	
1. Blocks	Group thematically related elements for better understanding.
2. Embedded Instruments	Embed an existing instrument into another one.
Descriptive Elements	
3. Headline	Introduces the following elements.
4. Text	Provides additional information to assist participants.
5. Media	Provides additional media information (e.g., images) to assist participants.
Data Collection Elements	
6. Question Types	
6.1. DropDown	Only one item may be selected.
6.2. Single Choice	Only one item may be selected.
6.3. Yes No Switch	Only one item may be selected.
6.4. Range	Multiple items may be selected.
6.5. Multiple Choice	Multiple items may be selected.
6.6. Ranking	Items may be ordered according own preferences.
6.7. Distribution	Points may be spent among available items.
6.8. Slider	One value from a predefined range may be selected.
6.9. Freetext	Answer using regular text input (text, number, date).
7. Sensor Types	
7.1. Camera	Take a picture during data collection.
7.2. Microphone	Record audio during data collection
7.3. Pulse Sensor	Measure the pulse rate during data collection.

Table 2.1: Frequently Used Basic Elements Within Instruments

used to guide participants through the data collection procedure. To collect data from participants, common *question* and *answer types* are used. Moreover, *blocks* that allow thematically structuring instruments were found in manifold situations. Furthermore, blocks may comprise the previously mentioned elements (e.g., headlines, questions). Especially in medicine and psychology, several considered instruments were *hierarchically structured* in order to allow comparing collected data amongst other datasets. Finally, specific control structures could be discovered that had been used to represent the logic, like `if-then-else` statements (e.g., *"If you answered this question with 'yes', please continue with Question 15, otherwise continue below."*) and `loops` (e.g., *"Please indicate the diseases that were diagnosed for all your siblings."*).

Fig. 2.1 illustrates a *validated* paper-based instrument for detecting risk factors during pregnancy [84], which has been successfully applied in various scenarios. In particular, data is collected following a standardized procedure, i.e., pregnant women fill in the questionnaires, while waiting for their consultation with the physician. Fig. 2.1 provides annotations for the aforementioned *descriptive* and *data collection* elements.

Instrument Modes

Depending on the application scenario an instrument is used, various *modes* for collecting data may be applied. On one hand, data is often collected with *self-report* questionnaires in medical trials [20]. The participant, thereby, processes the instrument autonomously, with no further assistance from staff members. In corresponding scenarios, additional information on how to properly process respective instrument must be provided to guide users through the process of data collection. This may include instructions on how to navigate within the instrument as well as texts on how to answer specific questions (e.g., to indicate specific body parts the participant was hurt). On the other hand,

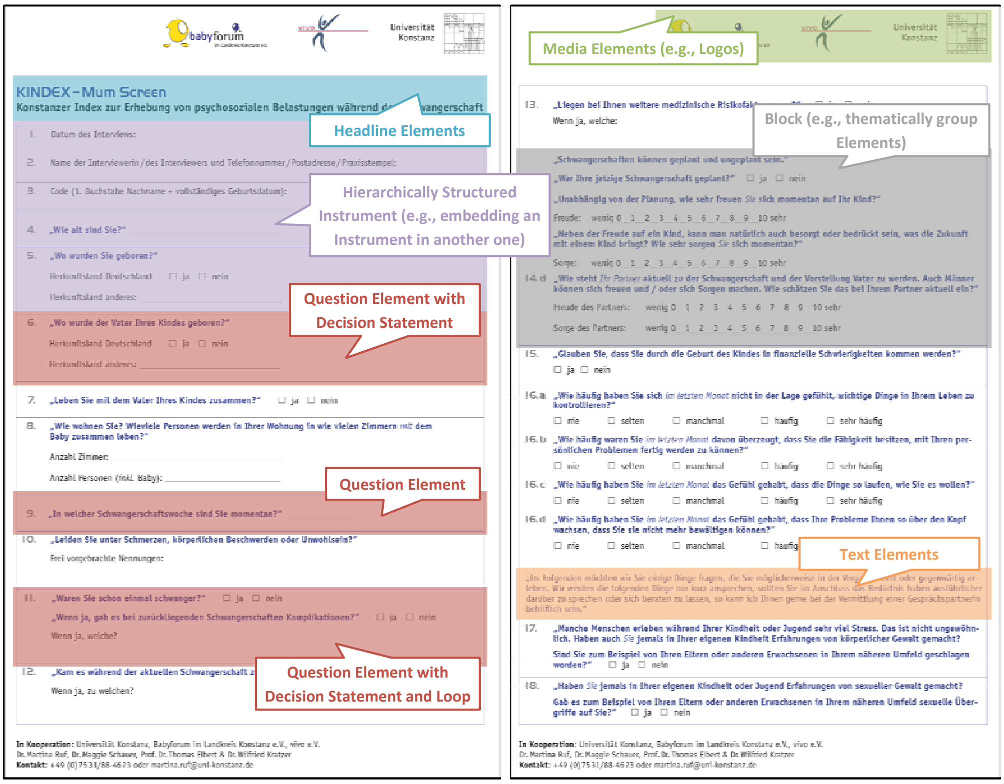


Figure 2.1: Example of a Validated Paper-Based Psychological Instrument [84]

psychological studies often collect data based on *interviews*, i.e., domain experts interact with participants to collect required data. Moreover, interviews may have to be flexibly adapted to the respective participants or their situation (e.g., a participant may want to talk about *drug abuse* first, before answering questions on his *childhood experiences*), or based on already given answers (e.g., the block dealing with *drug abuse* may be skipped if the participant does not take drugs).

Table 2.2 summarizes the findings obtained from the analysis of well-established instruments from various application domains.

2.2 Business Process Management

Process-Aware Information System

Process Schema

Contrary to traditional information systems, *Process-Aware Information Systems* (PAIS) [78] separate process logic from application code. The latter is accomplished by relying on a *process schema*, which provides a common interface for executing a large number of processes [79]. Such a process schema may be defined with different notations (e.g., graphs, constraints), each having their own peculiarities and application domains. As

Domain	Analyzed Instruments	Mode	Multiple Languages	Multiple Versions	Complex Navigation	Decisions	Loops	Embedded Instruments	Require Sensors
Psychology	11	B	●	●	●	◑	○	◑	○
Healthcare	9	B	●	●	●	●	◑	◑	◑
Logistics	4	S	○	○	◑	◑	○	○	◑
Automotive	5	S	●	●	●	●	◑	○	◑
Finance & Taxes	4	S	●	●	◑	◑	○	◑	○
Education	6	I	○	◑	◑	◑	○	○	○
Tourism	5	S	●	◑	○	○	○	○	○
Retail	4	S	○	○	◑	◑	○	○	○

● = almost every instrument; ◑ = some instruments; ○ = almost no instrument;

Mode: Different modes for answering an instrument (S = mostly Self-Rated; I = mostly Interviews; B = both).

Multiple Versions: There exist multiple versions of the same instrument at the same time.

Complex Navigation: The instrument comprises complex branching logic based on already given answers or pre-defined rules.

Embedded Instruments: Instruments are hierarchically structured (e.g., an existing instrument is used within another one).

Table 2.2: Findings when analyzing Instruments from various Domains

graph-based modeling notations (e.g., BPMN 2.0 or EPC) are common in both industry and science, the figures presented in this thesis are consequently represented with the *Business Process Modeling and Notation* (i.e., BPMN 2.0) [60].

Process Model

A process schema is specified through a process model. In this thesis, a *process model* P is represented as a directed, structured graph that consists of a set of *nodes* N and a set of directed *edges* E connecting them. A node either may represent an *activity*, or a *gateway* (e.g., `AND`, `XOR`) to allow expressing a more complex behavior. Each process model has exactly one *start node* and exactly one *end node*. Furthermore, the process model needs to be connected; i.e., each node n can be reached from the start node; likewise, the end node can be reached from each node n. *Data elements* D correspond to variables connected to nodes, which may then *read* or *write* corresponding values during process execution. Process models are usually created at *design time*.

Design Time

Block-Structure

Extensible Markup Language

As a prerequisite, a process model P must be *block-structured* (i.e., well-formed), i.e., each block spanned by a gateway has a single entry and a single exit point of the same type (e.g., `AND`). In general, blocks may be arbitrarily nested, but must not overlap each other (cf. Fig. 2.2). Note that this structure is similar to the one of *XML* documents.

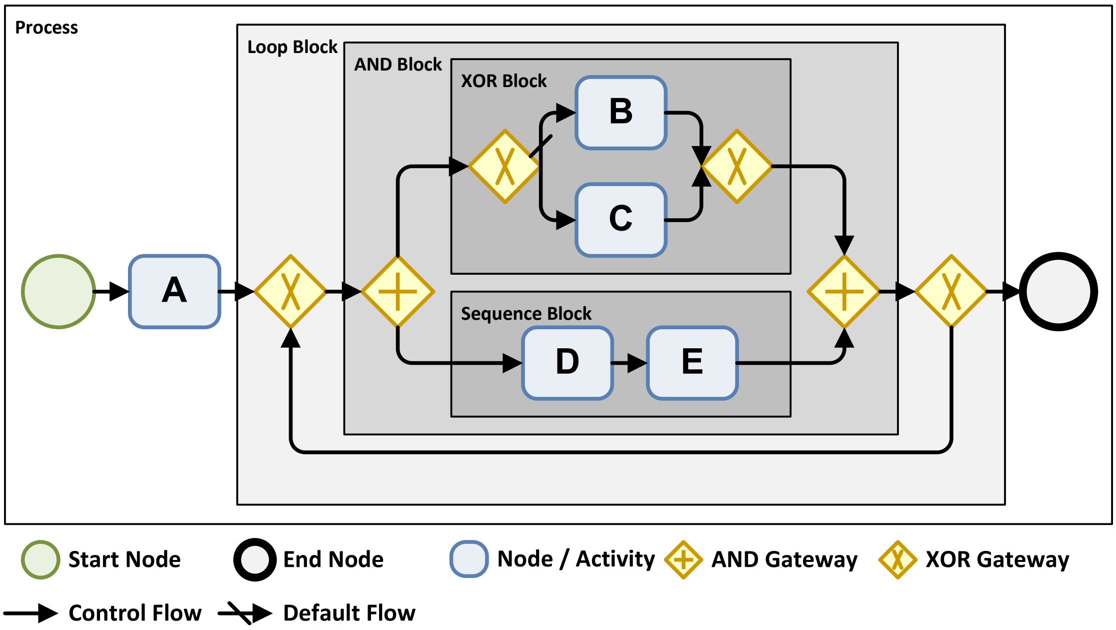


Figure 2.2: Block-Structured Process Model (using the BPMN 2.0 Notation)

During *run time*, a PAIS creates a *process instance* I for each (business) process to be executed. Such a process instance is then executed according to its predefined process model P as well as a generic set of execution rules [128]. The current state of one particular process instance is expressed through the markings of its nodes (e.g., `STARTED`, `EXECUTED`) and edges. Furthermore, data element values are stored in log files to properly reflect the execution history of one particular instance. In general, a PAIS is able to execute multiple instances of different models concurrently.

Run Time

Process Instance

2.3 Mobile Data Collection

Over the last decades, in many application domains large amounts of data were collected with paper and pencil. Due to the described drawbacks of this traditional approach, domain experts crave for more convenient approaches supporting their data collection procedures in daily life. More specifically, the digitization of an instrument should cover emerging demands from domain experts, like the support of an expressive navigation logic or the integration of *sensor data* (e.g., pulse sensor, GPS location, microphone, or camera) enhancing the expressiveness of the data collected.

In line with this trend, a multitude of web-based questionnaire applications have been developed. In particular, some of them specifically aim to support sophisticated data collection scenarios (e.g., in medical and psychological trials). Although many of these *web-*

Web Application

based applications have proven their applicability in a variety of application scenarios, they have been unable to cover all relevant use cases. For example, web-based questionnaires require a stable Internet connection (i.e., they do not work in offline mode), or might be unable to interact with external sensors (depending on the features of respective web browser).

Short Message Service

In the early 1990s, [22] evaluated the applicability of a handheld computer for data collection purposes in healthcare scenarios. In particular, a significant decrease in time needed for collecting data as well a significant increase of data quality could be observed. In 2004, [1] investigated whether or not mobile phones can be used for properly collecting data from patients on a daily basis. On one hand, *SMS* messages were used to remind patients about their medication or to ask them about their current status. On the other, the patients were asked to reply to the questions via SMS as well. As a result, the applicability of corresponding devices for mobile data collection scenarios on a daily basis was successfully demonstrated.

Mobile Data Collection

The aforementioned approaches have been adopted to smart mobile devices (e.g., smartphones or tablets) by enterprises and research projects in the large scale (cf. Chapter 7). Often, the term *Mobile Data Collection* describes this behavior. In 2009, [75] showed that smartphones act as a valuable device for leveraging data collection capabilities. In recent years, numerous mobile data collection applications were developed that allow domain experts (e.g., researchers) to collect data in a more convenient fashion.

2.4 End-User Programming

End-Users

In the era of digitization, more and more software applications will be developed, customized, and maintained by non-professional programmers. According to [91], approximately 90 million US citizens perform basic programming tasks in their job. In turn, [41] distinguishes between *professional* and *non-professional* programmers depending on their intention and motivation. For example, code written by non-professional programmers might not meet high quality standards, but is of a rather opportunistic nature. Such individuals are called *end-users* in the following.

End-User Programming

The term *End-User Programming (EUP)* summarizes sophisticated techniques that shall empower end-users with little (or no) programming knowledge to develop their own software applications. Respective approaches allow end-users to perform complex operations on their data, to run jobs in an easy-to-understand manner, or to design sophisticated user interfaces without need to learn any complex programming language. Examples of such end-user developed applications range from simple Wiki applications, which enable end-users to document tasks, to simplified database query languages (e.g., *Query by Example* applications), to sophisticated 3D modeling applications [67].

According to [90], the most popular end-user programming approach are spreadsheet-like applications, which are frequently used in enterprises to automate tasks or raise productivity (e.g., [121]).

Over time, a variety of end-user programming approaches, each providing their own (graphical) language, have emerged. *Graphical notations* rely on visual elements that may be interlinked by end-users to create a software application. Such elements represent specific code constructs (e.g., `loops` or `if-then-else` statements) or basic functions (e.g., `sum()`, `concatenate()`, or `append()`) that may be flexibly composed. The *textual representation* of the source code is hidden from users. Sophisticated wizards guide untrained users to reduce complexity and, hence, errors. Experiments conducted with pupils compared *graphical programming approaches* with common *textual* ones. Teachers reported that the graphical representation significantly improved the understanding of program code [39]. *Domain-Specific Languages (DSLs)*, in turn, try to abstract from complex programming languages and provide a rather limited, but easy-to-use syntax for end-users. Common examples are query languages for databases that are mapped to *SQL*. Experts from specific domains may use their domain-specific terminology instead of a generic terminology as known from common programming languages.

Domain-Specific Language

Structured Query Language

In a broader scope, *End-User Development (EUD)* covers additional phases of the software development lifecycle (e.g., requirements engineering, testing or documentation).

End-User Development

Although end-user programming approaches shall enable non-professional programmers to develop applications themselves to a certain extent or to adapt existing ones to their specific needs, there also exists criticism for respective approaches [29]. This includes arguments like *outsourcing* efforts to end-users instead of properly paying skilled application developers or *security concerns* regarding applications developed by non-programmers.

From a business perspective, end-user programming shows significant benefits. On one hand, end-user programming approaches contribute to reduce the *Business-IT alignment gap* (i.e., domain experts are unable to describe what a developer shall realize) as domain experts are empowered to actively participate in the process of developing software applications [12]. On the other, minor changes on an application can be accomplished by domain experts themselves (e.g., by adapting configuration files), relieving application developers from costly and time-consuming code adaptations.

3 Development Strategies

This chapter summarizes existing approaches for developing mobile data collection applications. An overview is provided by Fig. 3.1.

When developing mobile applications that support domain experts in collecting large amounts of data in a convenient fashion, various strategies can be applied. The latter, in turn, need to meet the requirements raised in the various application domains (e.g., in healthcare *"the data needs to be stored in a secure way and must not be accessible for unauthorized users"*.) ⓐ. Furthermore, the requirements specific to a given setting must be met (e.g., the application must not rely on a stable Internet connection) ⓑ. Finally, requirements related to technical aspects (e.g., the mobile platform or the integration of external sensors to collect additional data) ⓒ need to be covered.

Three core development strategies exist: First, one may develop a specifically tailored mobile application ① that meets the given requirements. Accordingly, the structure and logic of an instrument is directly *translated* to user interface elements of the respective mobile platform. To relieve application developers from implementing the same application for multiple platforms (e.g., Android and iOS may need to be covered properly), *cross-platform development* frameworks may be used [106]. Corresponding frameworks usually rely on web technologies (e.g., HTML, CSS and JavaScript) that are executed within a web container. This container provides native APIs to interact with the smart mobile device (e.g., access the camera of the device). Changes of an instrument (e.g., add or remove elements) result in code adaptations and, consequently, the new application needs to be deployed to and installed on the respective smart mobile devices. Finally, a sophisticated release management is required if several versions of an application are available concurrently.

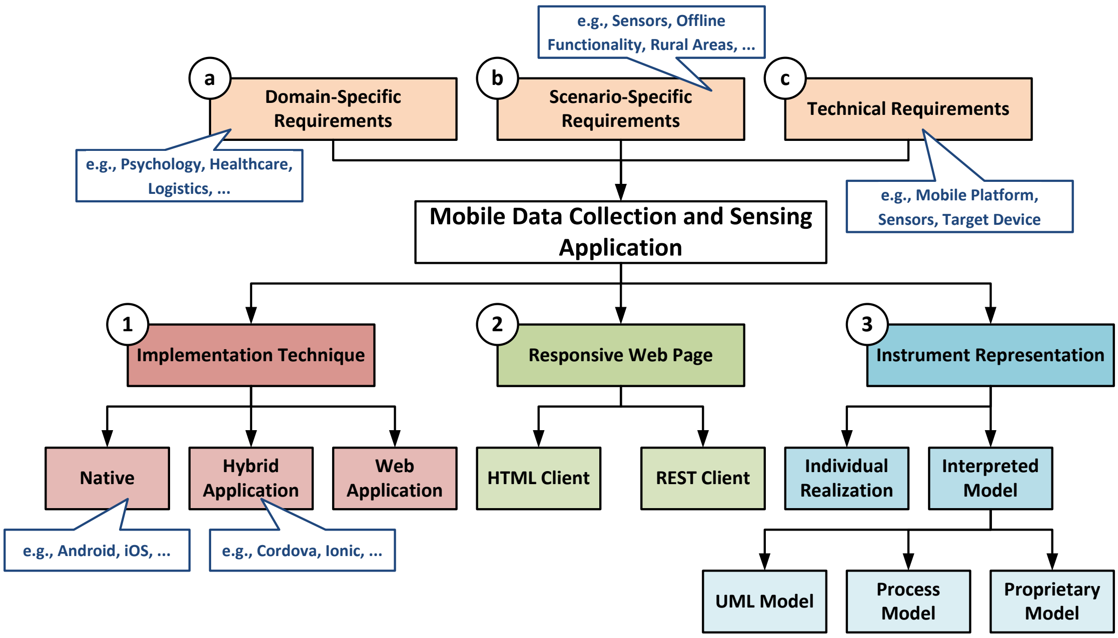


Figure 3.1: Strategies for Developing Mobile Data Collection Applications

As second strategy, one can develop a web page based on *responsive web design* practices ② to implement the instrument. Such techniques, in turn, allow quickly develop applications that may adapt the user interface of web pages according to the device. More specifically, CSS media queries may be used to switch styles accordingly [11] and present content adequately on smart mobile devices. As responsive web pages are accessible on a desktop computer, the instruments are available on all platforms being able to run modern web browsers. Instead of HTML, one may return a structured representation of an instrument. For web applications, *JSON* is commonly used as a lightweight data exchange format, which is easy to understand and use in the context of JavaScript applications [59]. Data provided by a *RESTful* server may be consumed and processed by a modern JavaScript application. However, the participant interacting with the instrument still uses a web application with all its limitations.

JavaScript Object Notation

Representational State Transfer

The third strategy represents an instrument in terms of specific models ③. The QuestionSys framework developed in this thesis applies techniques from this category. More specifically, *process models* are used to describe the structure and logic of a data collection instrument. Note that other models may be used for this purpose as well. For example, *UML* provides various (graphical) notations to describe the structure of an application as well as its control flow within specific components. Generators, in turn, may automatically transform the latter to code fragments, which can then be executed on corresponding devices. Finally, other (proprietary) models may be used in this context as well.

Process Model

Unified Modeling Language

Part II

The QuestionSys Framework

Core contributions presented in this part were mainly published in the following articles:

SPSR16 J. Schobel, R. Pryss, M. Schickler, and M. Reichert. A Lightweight Process Engine for Enabling Advanced Mobile Applications. In *24th Int'l Conf on Cooperative Information Systems (CoopIS)*, number 10033 in LNCS, pages 552–569. Springer, October 2016

SPSR16a J. Schobel, R. Pryss, M. Schickler, and M. Reichert. A Configurator Component for End-User Defined Mobile Data Collection Processes. In *Demo Track of the 14th Int'l Conf on Service Oriented Computing (ICSOC)*, October 2016

SPWSR16 J. Schobel, R. Pryss, W. Wipp, M. Schickler, and M. Reichert. A Mobile Service Engine Enabling Complex Data Collection Applications. In *14th Int'l Conf on Service Oriented Computing (ICSOC)*, number 9936 in LNCS, pages 626–633, October 2016

SPSRER16 J. Schobel, R. Pryss, M. Schickler, M. Ruf-Leuschner, T. Elbert, and M. Reichert. End-User Programming of Mobile Services: Empowering Domain Experts to Implement Mobile Data Collection Applications. In *5th IEEE Int'l Conf on Mobile Services (MS)*, pages 1–8. IEEE Computer Society Press, May 2016

The original articles are added to the Appendix of this thesis.

4
Concept

The main goal of the QuestionSys framework is to enable domain experts (e.g., medical doctors or psychologists), having no programming skills, to develop sophisticated mobile applications on their own. These applications, in turn, may then be used to collect data in large-scale scenarios like clinical trials or psychological studies [114]. Moreover, the deployment and execution of these applications on smart mobile devices shall be possible without help of any IT expert. On one hand, this shall reduce the costs and time required to develop and deploy data collection applications. On the other, the quality of collected data shall be increased.

Fig. 4.1 sketches the overall approach the QuestionSys framework realizes. A sophisticated configurator is provided that relies on *end-user programming* techniques to guide untrained users through the process of creating mobile data collection applications ①. To properly support untrained experts, a *Domain-Specific Language* for modeling instruments is introduced, hiding most of the complexity emerging during the development process and allowing for an easy-to-use approach.

End-User Programming

Domain-Specific Language

Each instrument modeled with the configurator, in turn, is mapped to a *process model*. As described earlier, process management technology acts as a solid technical foundation for the QuestionSys framework in general ②. On one hand, a process model specifies the control flow of the instrument (e.g., the order and constraints for processing the questions of an instrument). On the other, the process model enables a platform-independent representation of the instrument, e.g., no information on the user interface or the formatting of the instrument are included. Note that this approach is similar to the ones proposed in the field of *model-driven development*.

Process Model

Model-Driven Development

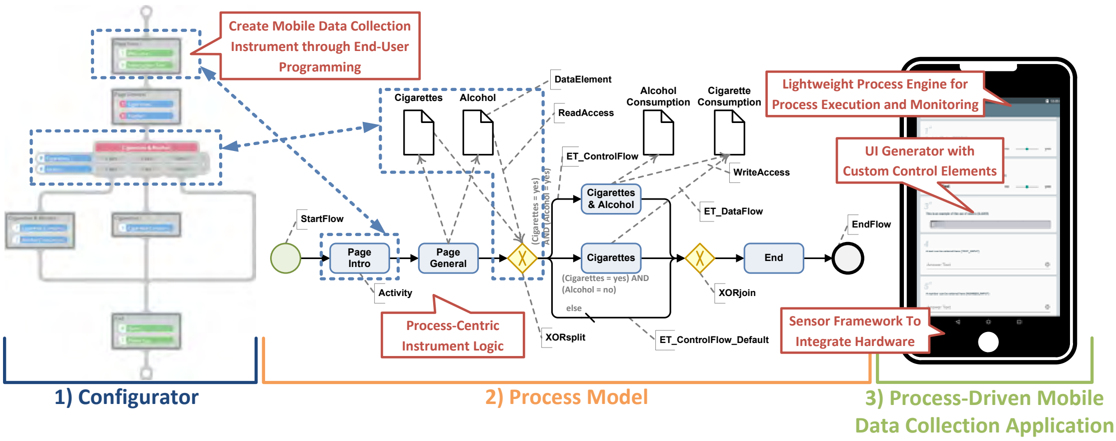


Figure 4.1: Model-Driven Development of Mobile Data Collection Applications

Process Engine

The derived process model may then be deployed to smart mobile devices. The latter comprise a *run time environment* (i.e., a *process engine*) that allows for the robust enactment of data collection instruments ③. The run time environment may further provide application-specific features, like the integration of *sensors* or the *on-demand evaluation* of collected datasets.

4.1 Requirements

In the context of this thesis, more than 50 established instruments from different domains were analyzed. This includes, for example, instruments from *psychology* (e.g., mental issues, drug abuse), *healthcare* (e.g., patient information), *automotive industry* (e.g., TÜV[1] vehicle inspection), and *finance* (e.g., tax declaration). Their analysis revealed requirements that are fundamental for the digitization of any instrument [107] and thus need to be properly covered by mobile data collection applications.

Post-Traumatic Stress Disorder

Depending on the scenario in which a mobile data collection application shall be applied, it might be crucial to enable its *offline* use as well. For example, when supporting researchers in collecting data related to *PTSD* in rural areas in Africa no stable Internet connection was available [108]. The psychological instruments used in this scenario as well as the data collected, had to be stored in a *secure* (e.g., encrypted) way on the smart mobile device. Furthermore, instruments may be processed using different *presentation modes* (e.g., interview vs. self-rating), having an impact on how questions are presented to participants, answers are selected, or the instrument itself is executed (e.g., if the participants are allowed to navigate within the instrument). Moreover, participants

[1] Technischer Überwachungsverein (Technical Inspection Association), a company that provides inspection and product certification services.

should be enabled to select the *language* the instrument is presented, to one that suits them best. Collected data, in turn, shall be *automatically evaluated* based on predefined rules. To only grant authorized users access to the collected data as well as the rules applied to the latter, a complex *user management* needs to be provided by the mobile application. Moreover, domain experts without programming skills shall be able to flexibly *adapt* the structure of an instrument (e.g., by adding questions or changing labels). In this context, it is crucial to always ensure the *validity* of the instrument at all time. Finally, the developed mobile data collection instruments shall be available on both prevailing *mobile platforms* (i.e., Android and iOS).

Obviously, the presented requirements adhere to different *phases* of the data collection procedure.

4.2 Mobile Data Collection Lifecycle

Insights from realizing long-running, real-world mobile data collection applications revealed a generic *lifecycle*. In order to properly assist the experts in collecting data in their specific application scenarios, the QuestionSys framework covers the entire *Mobile Data Collection Lifecycle*. The latter consists of 5 phases as illustrated in Fig. 4.2. *Lifecycle*

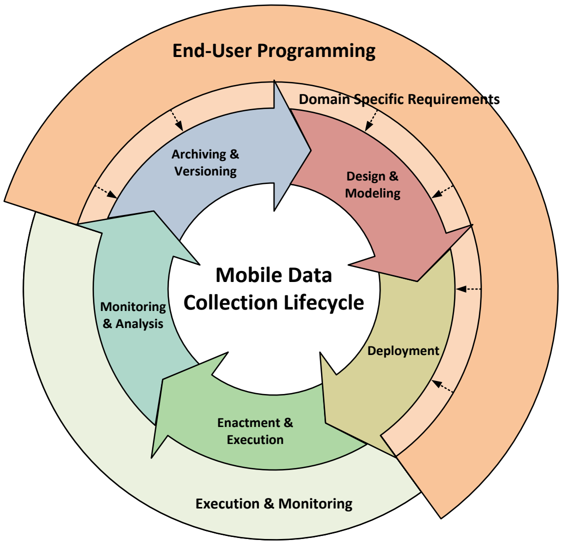


Figure 4.2: Mobile Data Collection Lifecycle

In the *Design & Modeling* phase, mobile data collection instruments with complex navigation logic are created by domain experts. The *Deployment* phase, in turn, allows for a secure and robust deployment of the created instruments to smart mobile devices. During the *Enactment & Execution* phase, multiple instances of the previously deployed data collection instrument may be created and executed on the smart mobile devices to collect data in a convenient fashion. The *Monitoring & Analysis* phase deals with the real-time analysis of the data collected on the smart mobile device. Finally, the *Archiving & Versioning* phase provides sophisticated techniques for managing different releases of a modeled data collection instrument as well as for archiving the collected data. In order to adequately support domain experts in modeling sophisticated mobile data collection instruments as well as to meet domain-specific requirements, end-user programming techniques are applied in certain phases of the lifecycle.

4.3 Model-Driven Development of Instruments

Model-Driven Development

To address the discussed requirements and to provide an approach supporting the entire lifecycle of an instrument, the QuestionSys framework follows a *model-driven approach*, which consists of four models (cf. Fig. 4.3). Thereby, a model is continuously transformed into another one by enriching the former with additional information. Furthermore, platform-specific information may be added to tailor models to specific operating systems or execution environments. Finally, code is automatically derived from this information [10]. Often, *UML* is used in this context as a vendor-neutral standard [86].

Unified Modeling Language

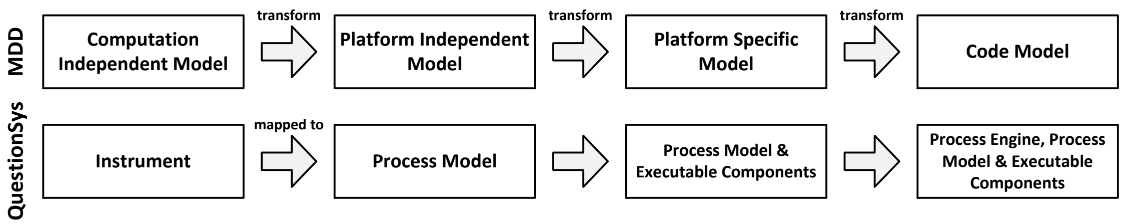


Figure 4.3: Aligning the QuestionSys Approach to Model-Driven Development

As discussed, the QuestionSys framework describes the logic of a data collection instrument in terms of a *process model* (cf. Fig. 4.4), which is enacted by a lightweight process engine running on heterogeneous smart mobile devices [112, 115].

Further, QuestionSys allows *mapping* instruments to executable process models. More specifically, the content and logic of paper-based instruments can be mapped to a process model. In more detail, *pages* of an instrument correspond to *activities* within the process, whereas the *flow* between activities matches the *navigation logic* of the instrument. *Questions* are mapped to *data elements*, which, in turn, are connected via `WRITE` *data edges* to respective *pages*. A *data element* stores an answer given during the execution of the model on the smart mobile device. Sophisticated *navigation logic* can be specified using *gateways* (i.e., `READ` specific *data elements*). Fig. 4.5 illustrates the described

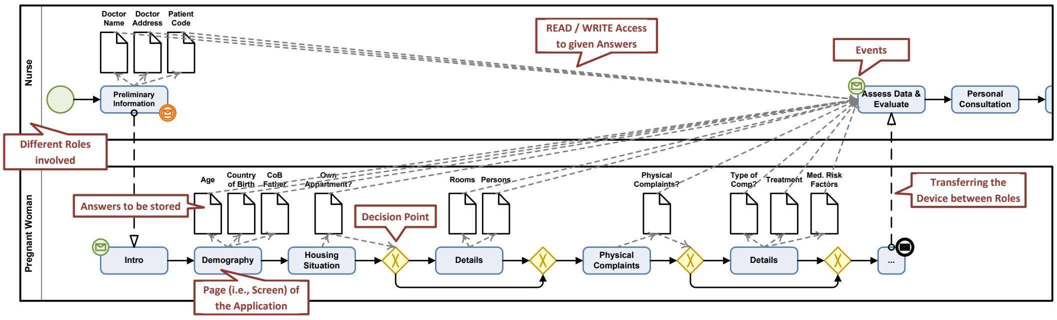


Figure 4.4: A Psychological Instrument Represented as BPMN 2.0 Model

mapping from a paper-based instrument to a process model, and the subsequent execution of this model by a lightweight process engine running on a smart mobile device. Currently, the QuestionSys framework relies on ADEPT2 [42, 77], but can be easily adapted to other meta-models (e.g., *WS-BPEL* [127]) as well.

Business Process Execution Language

Applying an established *process modeling notation* (e.g., BPMN 2.0 or EPC) for specifying the logic of an instrument has proven to be useful. In general, however, aspects other than the *control flow* need to be considered as well [89], e.g., the *data flow* [87], *resource* [88], and *time* [44, 46] perspectives. When applying graphical notations for modeling data collection procedures, additional issues emerged. For example, domain experts were overwhelmed by the multitude of graphical elements (as well as their semantical meaning) to properly represent their data collection instrument [136], e.g., dealing with *data elements* and corresponding *data flow* was especially challenging for non-modeling experts.

Domain-Specific Language

To address these revealed issues, a novel graphical *domain-specific language* is proposed. The latter relies on concepts known from BPMN 2.0, but omits elements not needed in data collection scenarios (e.g., temporal constraints [45] or business events [17]). Furthermore, the modeling of data elements has been simplified; i.e., data flow is implicitly modeled.

The QuestionSys framework provides a sophisticated configurator relying on this graphical notation to enable domain experts to model instruments in a convenient approach. This graphical notation, in turn, needs to be evaluated regarding its usability, especially when being used by domain experts having no experience with process modeling notations. Chapter 8 presents results from extensive studies addressing such usability aspects.

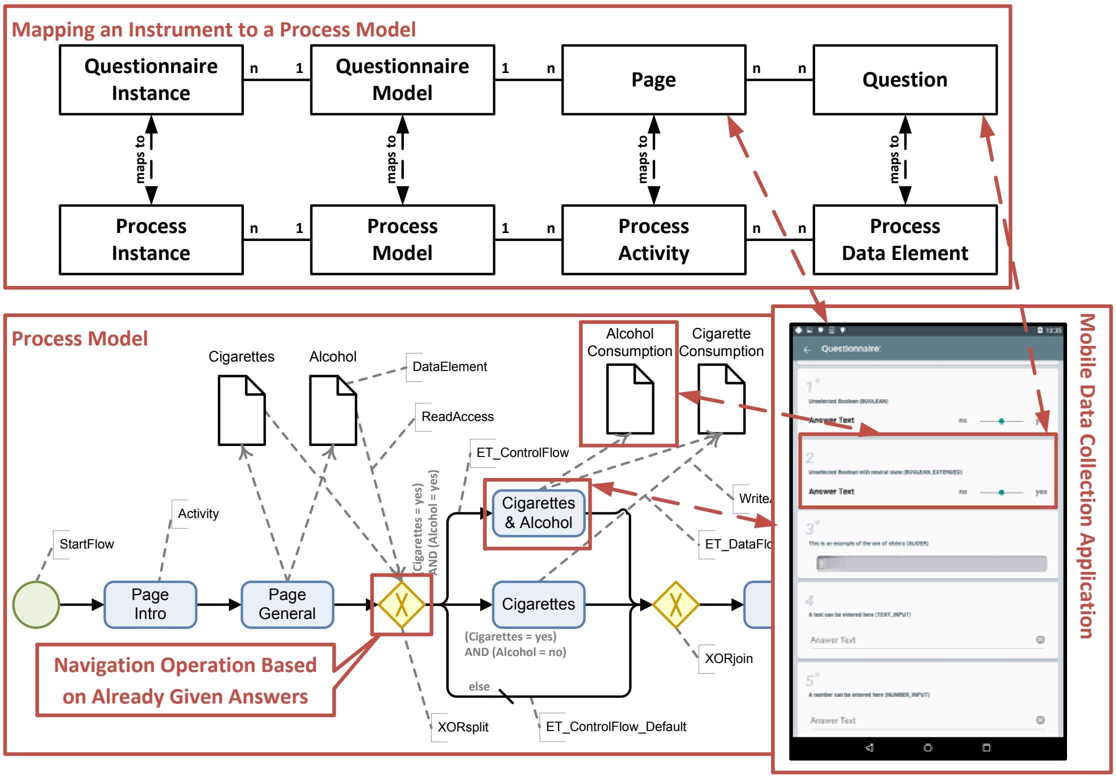


Figure 4.5: Mapping an Instrument to a Process Model and its Execution on a Smart Mobile Device

5 Architecture

This chapter presents the architecture of the *QuestionSys framework* and describes selected components (e.g., the *configurator* and *mobile client application*). Further, it presents the procedure of modeling, deploying and executing an instrument with the QuestionSys framework.

5.1 Architecture

The architecture of the QuestionSys framework applies a process-driven approach, i.e., it is driven by *process management technology* (cf. Fig. 5.1). *Business Process Management*

Creating data collection instruments based on process management technology: A domain expert can create a data collection instruments using a process-aware *configurator* ⓐ [113]. The latter, in turn, provides a domain-specific modeling language for graphically creating instruments. Furthermore, the configurator allows defining rules for automatically evaluating the collected data ⓑ (e.g., to calculate the *body mass index* of participants).

Generating mobile applications based on process models: The *process model* (i.e., the modeled data collection instrument) acts as a schema for the subsequent execution of corresponding instances by a lightweight mobile *process engine* that runs on various mobile operation systems [115]. By interpreting such models directly on the smart mobile device, changes to an instrument can be realized in a cost- and time-efficient manner. A sophisticated rendering algorithm not only takes different

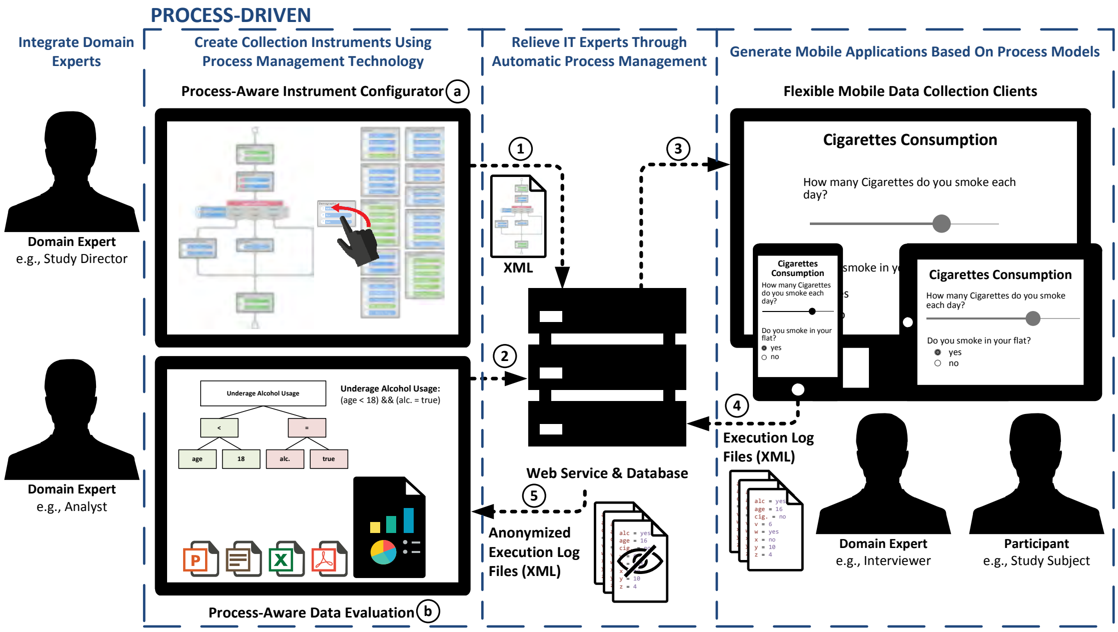


Figure 5.1: The QuestionSys Architecture

mobile operating systems into account, but also device properties (e.g., screen size) and the language to be displayed.

Relieving IT experts through automatic process management: The created instrument (i.e., the process model along with its rules for evaluating the data collected) is mapped to an *XML* document, which can then be deployed to available smart mobile devices. During the execution of instrument instances, collected data is stored directly on the smart mobile device. The QuestionSys architecture relies on *RESTful* Web Services [21] for realizing the communication between the components ①–⑤.

Extensible Markup Language

Representational State Transfer

The architecture in general and the procedure of deploying instruments to smart mobile devices, help mitigating several issues known from data collection projects [37]. Releasing a new version of an already existing data collection instrument, for example, does not require the involvement of mobile application developers anymore. Instead, domain experts themselves may apply the desired changes to the model and deploy its new version on a server component. Mobile data collection clients, in turn, can then download the new version and enact further instrument instances based on the new model.

In the following, core components of the QuestionSys framework are discussed in detail. Specifically, the configurator used for creating data collection instruments as well as the mobile client used for executing the latter are presented.

5.2 Process-Aware Instrument Configurator

The developed QuestionSys *configurator* allows domain experts with little or no programming skills or knowledge in process modeling to flexibly create data collection instruments on their own. More specifically, it applies *process management* concepts and technologies in a broader scope [85]. In this thesis, only the most relevant aspects of the configurator are presented (see [113] for an in-depth description of details).

Business Process Management

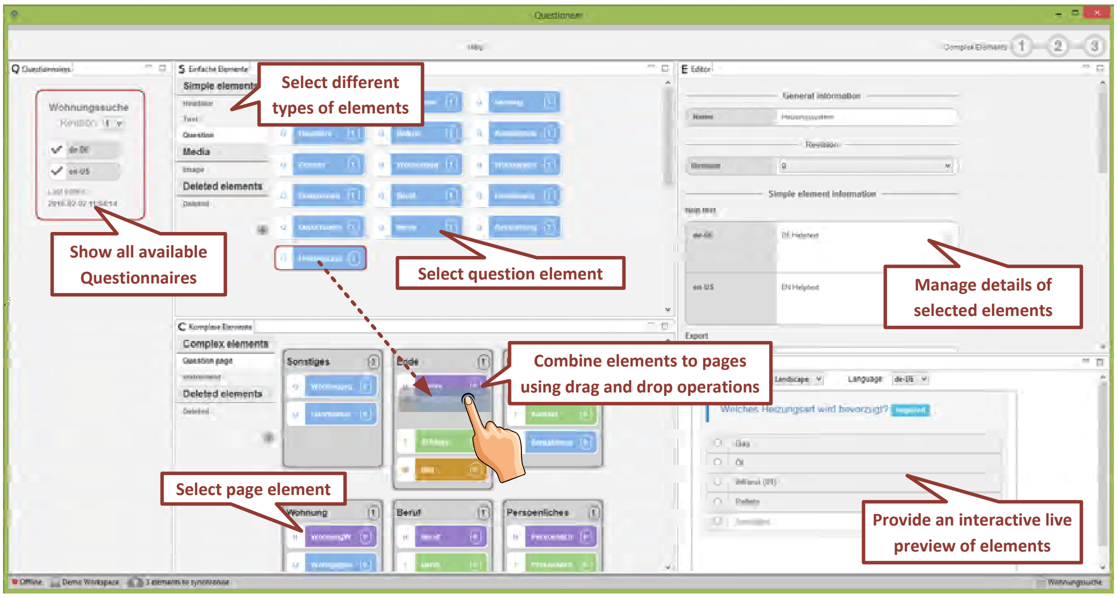


Figure 5.2: The QuestionSys Configurator

Figs. 5.2 and 5.3 show the user interface of the configurator. Fig. 5.2 depicts the *Element and Page Repository*, which enables domain experts to create basic elements of an instrument (e.g., headlines or questions). The latter may be further customized using an editor being able to handle multiple languages as well as to track different revisions of elements. Using drag and drop operations, elements may be combined to pages (i.e., one screen in the resulting mobile application). An interactive live preview, which allows simulating different mobile devices, provides immediate feedback to domain experts.

Fig. 5.3 illustrates the *Modeling Area* where the data collection instrument under development is visualized. More precisely, previously created pages may be dragged to the graph in the middle of the screen to define the structure and navigation flow of an instrument. In order to properly support untrained domain experts, a *correctness-by-construction* principle [16] is applied. The latter ensures that only currently valid operations can be applied to the model. Moreover, the model can be executed by the lightweight process engine at any time. Finally, a specifically developed *domain-specific modeling notation* is applied in order to simplify the modeling process.

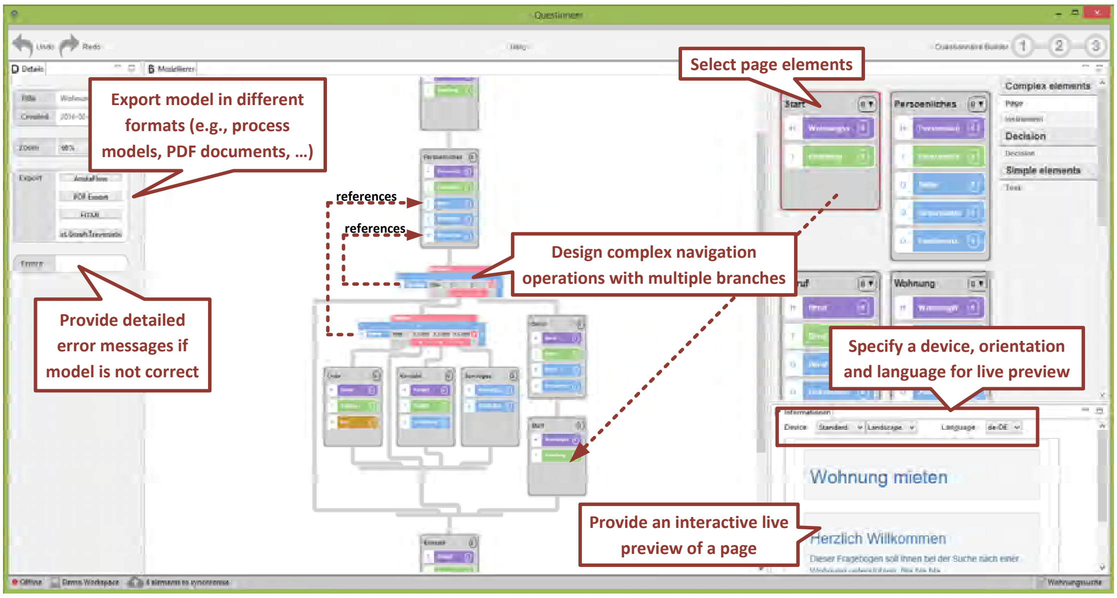


Figure 5.3: The QuestionSys Configurator

5.3 Flexible Mobile Data Collection Client

The *mobile data collection application* is a client that runs on multiple operating systems (i.e., Android or iOS). This application consists of basic interfaces for managing instruments, e.g., to download them from a server. Furthermore, it provides features for executing an instrument and, hence, collecting data based on the created model. In this thesis, a lightweight *process engine* running on smart mobile devices was developed. In particular, this engine enables a robust execution of data collection instruments, while providing the flexibility to enhance and adapt the provided functionality.

The lightweight process engine is designed as a service that may be embedded in other mobile applications as well. It provides a high-level communication interface to create new instances based on a given process model and to execute them according the specified logic of the instrument. The communication and data flow between the mobile data collection application and the process engine is illustrated in Fig. 5.4.

It is noteworthy that the process engine only handles the execution of the model itself. For example, it evaluates the *nodes* (i.e., pages) to be processed next or reads data from respective *data elements* and passes it to the *node*. However, the lightweight process engine is not responsible for processing the actual *content* of the page (i.e., for displaying the user interface to collect data). The QuestionSys framework defines and provides *Executable Components (ECs)* for the latter purpose. An EC can be seen as a *micro*

Executable Component

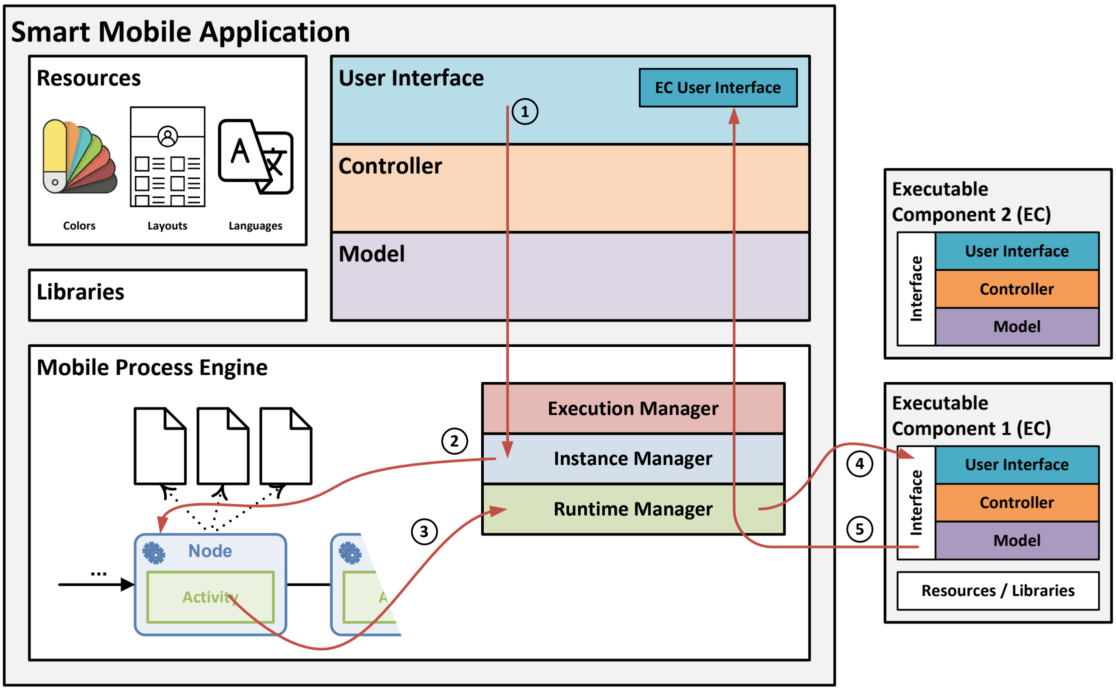


Figure 5.4: The QuestionSys Mobile Data Collection Client

service [58] which is self-contained, providing a limited functionality (e.g., rendering the specified user interface in order to collect data).

All available ECs are coordinated by the lightweight process engine. As depicted in Fig. 5.4, ECs are not part of the mobile data collection client itself, but are installed as separate applications on the smart mobile device. For example, the *Page* EC, which provides basic presentation logic, may be adapted independently from the mobile data collection application or process engine. Furthermore, an EC may be replaced by another one providing more functionality (e.g., to collect vital parameters via external sensors) or by changing the overall style of the user interface. Note that such a feature may be crucial depending on the context and application scenario in which the mobile data collection application is used. Altogether, this approach fosters the *separation of duties* and provides an easy-to-extend approach for mobile application development.

Note that the ECs and process engine communicate through well-defined interfaces. For example, the process engine may query the current status of an EC (e.g., to check whether all mandatory fields are filled in). Likewise, the EC may notify the engine if errors occur that need to be handled.

Fig. 5.5 shows the user interface of the developed mobile data collection client. Furthermore, it illustrates how specific parts of the user interface are rendered by different *parts* of the mobile data collection application (i.e., the main application and the ECs

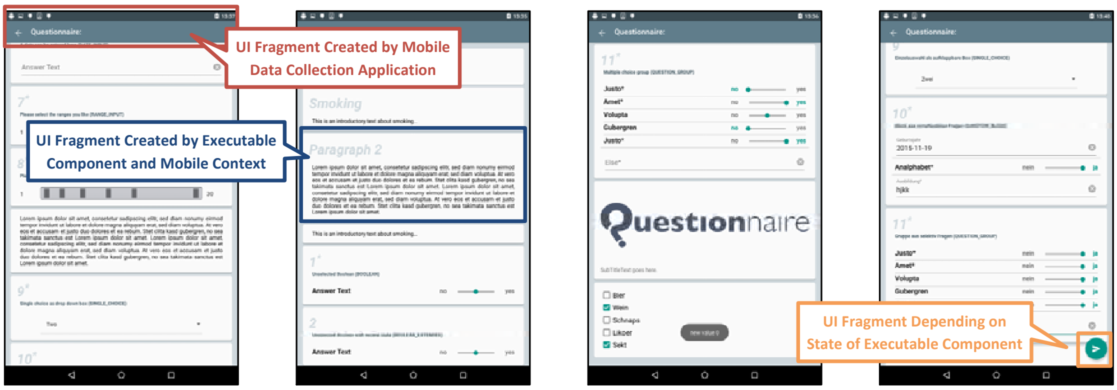


Figure 5.5: User Interface of the Mobile Data Collection Client

respectively). The *floating action button* to proceed to the next page of the instrument (cf. Fig. 5.5; rightmost part), for example, is only rendered if a corresponding `EC` notifies the process engine upon its completion. For the end-user interacting with the mobile data collection application, however, everything is combined into one interface, enabling a consistent user experience.

6 Discussion

This chapter discusses key aspects of the QuestionSys framework and relates them to requirements gathered in case studies from various domains.

The fundamental goal of the QuestionSys framework is to empower domain experts having no programming expertise to develop mobile applications for data collection purposes themselves. For this purpose, a sophisticated instrument configurator (cf. Fig. 6.1, ⓐ) was developed, which applies techniques known from *end-user programming* to guide domain experts through the process of modeling instruments.

When deploying an instrument, it is automatically transformed into a *process model* (cf. Fig. 6.1, ⓑ). This process model expresses the complex navigation logic of the instrument (e.g., via *gateways*), depending on the needs of the considered application. Furthermore, the process model specifies the *data flow* within the instrument (e.g., the data collected on a specific page of an instrument). To reduce the number of available graphical elements for modeling as well as the overall complexity during the modeling procedure, QuestionSys uses its own *domain-specific modeling language*.

After downloading an instrument to a smart mobile device (cf. Fig. 6.1, ⓒ) it can be executed with the lightweight process engine. This engine, in turn, is capable of dynamically executing instances of the instrument based on its process model in order to collect data in a convenient fashion. The concept of ***ECs*** allows flexibly adapting the provided functionality of the developed mobile data collection application. More specifically, ECs may be customized depending on the considered application scenario. Thereby, not only the visual appearance (e.g., colors) of the application may be changed, but also new control elements be introduced. Fig. 6.2 shows a specifically developed

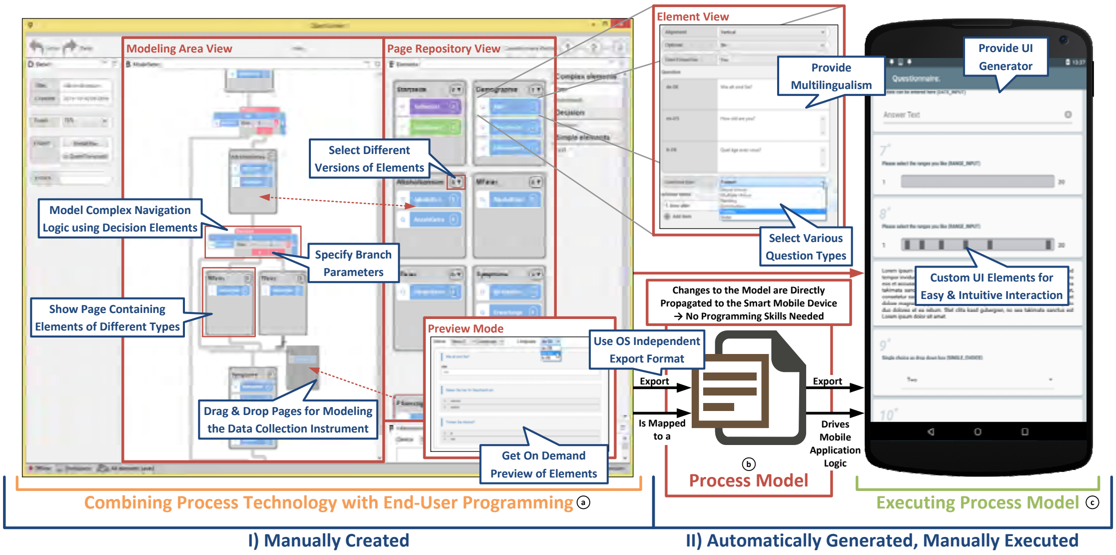


Figure 6.1: Empowering Domain Experts Developing their own Mobile Data Collection Applications

control element *Button Bar* that allows selecting appropriate values. This selection, in turn, is then displayed directly on the bar (i.e., the dark gray overlays).

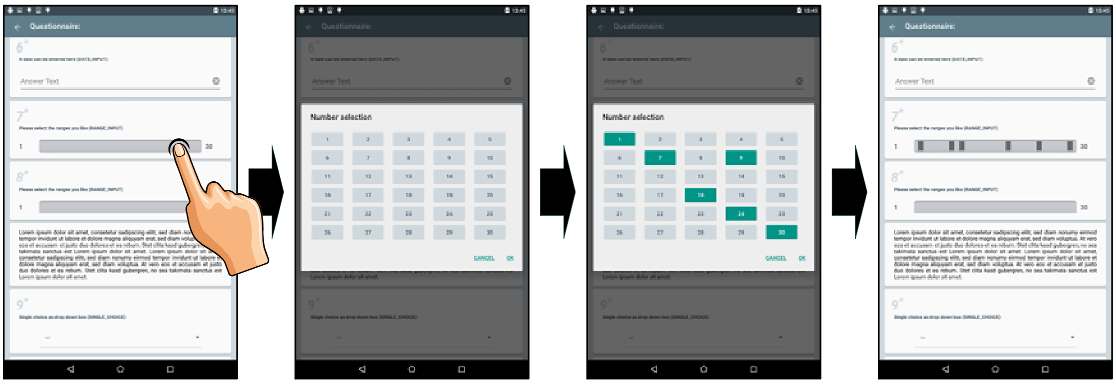


Figure 6.2: Implementing Custom UI Controls for Collecting Data

Note that changes applied to the instrument solely affect the model. QuestionSys relies on high-level *change patterns* describing frequently required operations, like inserting a new page to the instrument or moving elements within a page (cf. Table 6.1). These patterns support domain experts on a more abstract level to perform required adaptations to instruments. Further, they assure that the model is kept in a correct state, e.g., if a `SPLIT` gateway is added, the corresponding `JOIN` gateway is simultaneously added. After downloading the new version of the instrument, the adaptations become immediately available on respective smart mobile devices. Based on this approach, changes to data collection instruments no longer require the costly involvement of IT experts in the process of developing sophisticated data collection instruments.

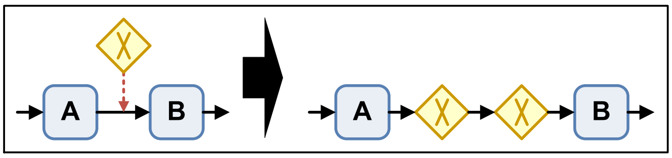
Name	Insert Block. Add a new block to an existing instrument. Available `types` are `IF`, `ALL`, and `REPEAT`.
Signature	`insertBlock(type, before, after)`
Example	Depending on the `type` of the block, various scenarios are possible: • `IF` blocks solely select *one path* based on already given answers during run time. • `ALL` blocks select *all paths* to be executed, however, the person interacting with the smart mobile device may choose its order of execution. • `REPEAT` blocks allow for repeating the content of the block multiple times. The amount of repetitions may be determined at run time (e.g., based on given answers) or are pre-defined by the domain expert (e.g., n times). 
Pre-Condition	The position to insert the `block` must be exactly specified; i.e., `after` must directly follow `before`.
Post-Condition	An empty block comprising a `split` and `join` gateway that are directly connected is inserted; For `IF` and `REPEAT` blocks, data elements for evaluating the conditions need to be connected using `READ` data edges.

Table 6.1: Example of a Change Pattern

The change patterns were evaluated in a *usability study* with 111 participants from various domains. During this evaluation, participants had to work with an early prototype application to apply change patterns to an existing data collection instrument (e.g., change the order of pages or insert new elements at specific positions).

Figs. 6.3, 6.4, and 6.5 provide insights of this study. More specifically, Fig. 6.3 evaluates the overall complexity of modeling data collection instruments. Fig. 6.4, in turn, illustrates the perceived complexity when applying specific change requests. Interestingly, most of the participants rated the modeling concept as easy or even better. When it comes to the modeling of complex navigation operations, however, participants reported problems (cf. Fig. 6.5). As illustrated, the perceived mental effort was considerable high for the majority of the participants. Consequently, the QuestionSys approach for modeling the navigation logic of an instrument (i.e., decisions) was refined in later versions of the framework. Finally, the evaluation compared the submitted models with a reference model designed by experts. Approximately 81% of the provided models were sound, whereas 64% of the *Psychologists* submitted correct models.

The presented QuestionSys approach guarantees flexibility along the various phases of the mobile data collection lifecycle [111]. In particular, through the combined use of

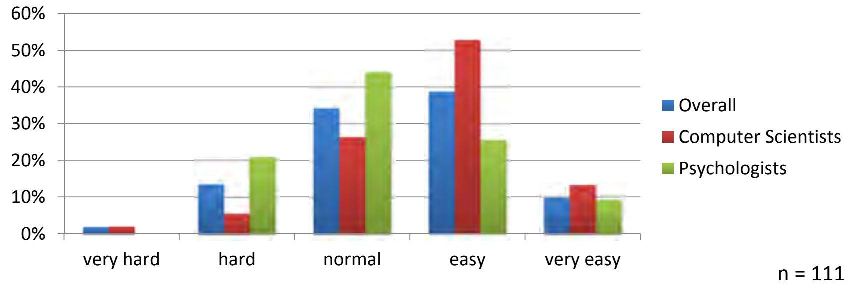


Figure 6.3: Perceived Mental Effort during Modeling

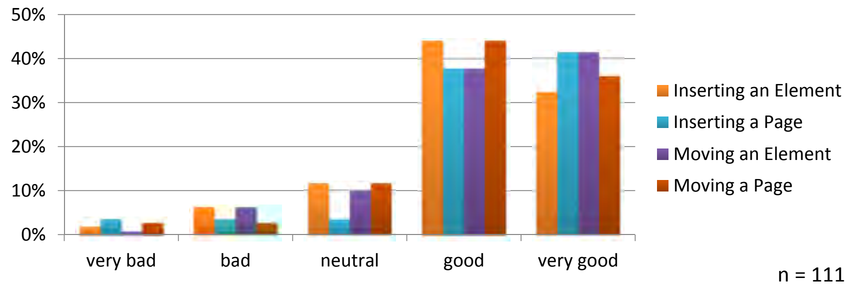


Figure 6.4: Perceived Mental Effort when using Basic Operations

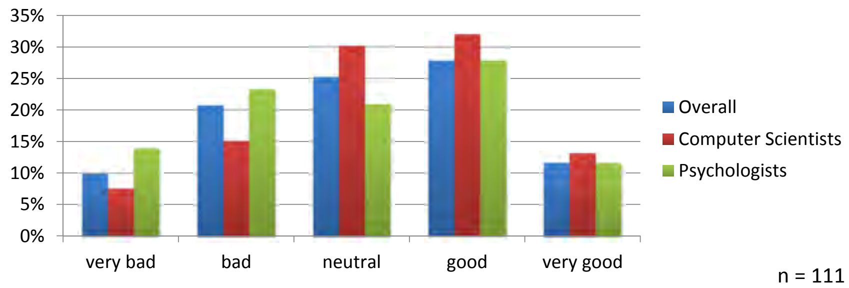


Figure 6.5: Perceived Mental Effort when using Complex Navigation Operations

well-established and standardized technologies, domain experts are empowered to create mobile data collection instruments without the involvement of any IT experts (cf. Table 6.2). Finally, requirements that were elaborated by ① analyzing instruments from various domains, ② conducting multiple interviews with domain experts, and ③ implementing mobile data collection applications for various scenarios are adequately addressed with the presented approach and corresponding architecture.

	Custom Modeling Language	End-User Programming	Process Model	Process Engine	Executable Components	Sensor Framework	Process Mining
Model-Based Approach	•	•	•	•			•
Complex Navigation	•	•	•	•	•		
Different Releases		•	•				
Flexible & Robust Execution			•	•	•		
Monitoring & Analysis			•	•	•		•
Sensors	•	•			•	•	
Multilingualism	•	•			•		
UI Generator					•		
Domain-Specific Requirements	•				•	•	
Evolution of Instruments	•	•	•	•	•	•	

Table 6.2: Combining Technologies Enabling Flexibility in Mobile Data Collection Scenarios

7 Related Approaches

This section discusses approaches from research and industry that are related to the QuestionSys framework. As there exists a plethora of such applications, only the most relevant approaches are discussed.

7.1 Research Approaches

In [32], a rather generic approach for developing applications that run on mobile operating systems is discussed. This approach allows mobile application developers to describe their application scenario, entities, and mobile device features with a meta-programming language. The models are then translated into native application code for iOS and Android. Furthermore, the approach automatically generates RESTful code for a server backend allowing mobile applications to store respective data online. As opposed to QuestionSys, most configuration is done in a textual way, neglecting the advantages of graphical notations. Based on these insights, the approach specifically targets at individuals being experienced with mobile application development.

Based on prior work, [81] describes a process-oriented approach for creating mobile business applications. In particular, the authors illustrate how their models can be transformed into application code running on different mobile operating systems. However, the graphically specified application logic is completely transformed to native application code, resulting in a specifically tailored mobile application. As a consequence, many promising key features known from process management technology research are not available. As opposed to the QuestionSys approach, these applications are limited with respect to the provided instrument features. In particular, advanced features like the process-driven navigation logic (e.g., influencing the further course of the instrument based on already given answers) are not provided.

What You See Is What You Get

A more sophisticated *WYSIWYG* editor for developing smart mobile applications in general is presented in [4]. Similar to QuestionSys, it relies on a model-driven approach that uses its own domain-specific language. These models are then transformed into native application code that runs on smart mobile devices. This approach, however, specifically targets at mobile application developers who shall be relieved from complex programming tasks. As a drawback, this approach does not involve domain experts.

Dynamic HTML

An approach involving end-users is proposed in [38]: medical staff is empowered to model care plans for chronically ill patients. These plans are then automatically transformed into *DHTML* applications and deployed to smart mobile devices. This way, specifically tailored mobile applications for individuals can be created. As opposed to the QuestionSys framework, however, the approach presented by the authors is *domain-specific*, i.e., its application scenario is limited to care plans.

A noteworthy approach is illustrated in [131, 132]. *WordPress*, a well-known blogging software, is combined with *iBuildApp*, a Web-based application builder, in order to create a platform supporting students from clinical psychiatry. The platform focuses on information retrieval for users (e.g., provide psychiatric guidelines). However, it also provides limited support for developing digital questionnaires to allow students to check their knowledge.

The research projects *Manage My Pain* [76], *TrackYourTinnitus* [64], and *PsychLog* [24] apply *crowdsensing* techniques for collecting vital healthcare data on a regular basis. These projects developed smart mobile applications for convenient data collection purposes. Compared to the QuestionSys approach, they only provide rudimentary configuration possibilities for instruments. In this context, *PsychLog* offers more sophisticated features for configuring data collection studies. This includes, for example, time-based triggers or instruments that may affect (e.g., exclude) each other.

7.2 Products

Hypertext Markup Language

Cascading Style Sheets

Along the trend of *no-code* (or *low-code*) approaches, which enable individuals to develop specific (mobile) applications, a number of software products emerged. For example, *WebRatio* [8], *Mendix* [33], or *OutSystems* provide model-driven platforms supporting non-developers in creating mobile applications. These models are then deployed to web platforms and smart mobile devices respectively. The applications, in turn, are created with common web technologies (e.g., *HTML5*, JavaScript, *CSS3*), which are rendered in a web browser. In consequence, only functionality available in modern web browsers can be used.

BuildFire[1] positions itself as a rapid development framework, which provides a sophisticated *WYSIWYG* editor to visually define mobile applications. Although the focus of this framework is not set on data collection in general, it still may be used for this purpose as well. Depending on the considered application scenarios the available user interface elements may have restricted functionality. More complex navigation logic for electronic forms requires adaptations on code level. By contrast, *Bubble*[2] uses *end-user programming* techniques to enable non-programmers to develop mobile applications. In particular, Bubble relies on a *workflow-based programming language*, which may be used by non-programmers. However, generating mobile applications based on this approach is in a premature stadium.

What You See Is What You Get

In the field of online *questionnaire applications*, a plethora of applications exist. Examples include *LimeSurvey*[3], *SurveyMonkey*[4], *Qualtrics*[5], and *SmartSurvey*[6]. These applications provide configurators that allow designing online surveys. However, the vast majority of applications rely on form-based editors, which are limited with respect to the design of navigation logic. There is no graphical *modeling* approach as provided by this thesis. Furthermore, questionnaires are usually filled in with a web browser. These web pages, in turn, are developed with *responsive web technologies* [23]; i.e., the user interface is properly adjusted depending on the respective device. Therefore, solely features provided by the web browser are supported.

MovisensXS, an online application targeting at *ambulatory assessments*, allows researchers to create instruments with a form-based editor. These instruments may then be executed on smart mobile devices. Compared to QuestionSys, the application does not allow for multilingualism. Instead a researcher would need to copy the instrument and change its labels. A noteworthy feature of movisensXS is the *sampling graph*, which allows researchers to properly define the way the study shall be presented on the respective devices. Specific triggers (e.g., time- or value-based) may be used to start instruments. Participants, in turn, get notified when the respective instrument needs to be processed. Such approach may be of particular interest in the field of *experience sampling*. Like QuestionSys, *movisensXS* applies a graphical notation for configuring the sampling graph.

Experience Sampling Method

[1]https://buildfire.com ; accessed 2018-03-12
[2]https://bubble.is ; accessed: 2018-03-12
[3]https://www.limesurvey.org ; accessed: 2018-03-12
[4]https://www.surveymonkey.com ; accessed: 2018-03-12
[5]https://www.qualtrics.com ; accessed: 2018-03-12
[6]https://www.smartsurvey.co.uk ; accessed: 2018-03-12

Part III

Validation

Core contributions presented in this part were mainly published in the following articles:

SPSPGSR17 J. Schobel, R. Pryss, W. Schlee, T. Probst, D. Gebhardt, M. Schickler, and M. Reichert. Development of Mobile Data Collection Applications by Domain Experts: Experimental Results from a Usability Study. In *29th Int'l Conf on Advanced Information Systems Engineering (CAiSE)*, number 10253 in LNCS, pages 60–75. Springer, June 2017

SPPSSR18 J. Schobel, R. Pryss, T. Probst, W. Schlee, M. Schickler, and M. Reichert. Learnability of a Configurator Empowering End Users to Create Mobile Data Collection Instruments: Usability Study. *JMIR mHealth and uHealth*, 6(6):e148, 2018

The original articles are added to the Appendix of this thesis.

8 Studies

To evaluate the applicability of the QuestionSys framework, various studies were conducted. On one hand, these studies evaluated how efficient participants work with the QuestionSys configurator. On the other, their mental effort for modeling tasks and the complexity perceived in this context were assessed. Finally, insights into the participants' process of modeling instruments were gained.

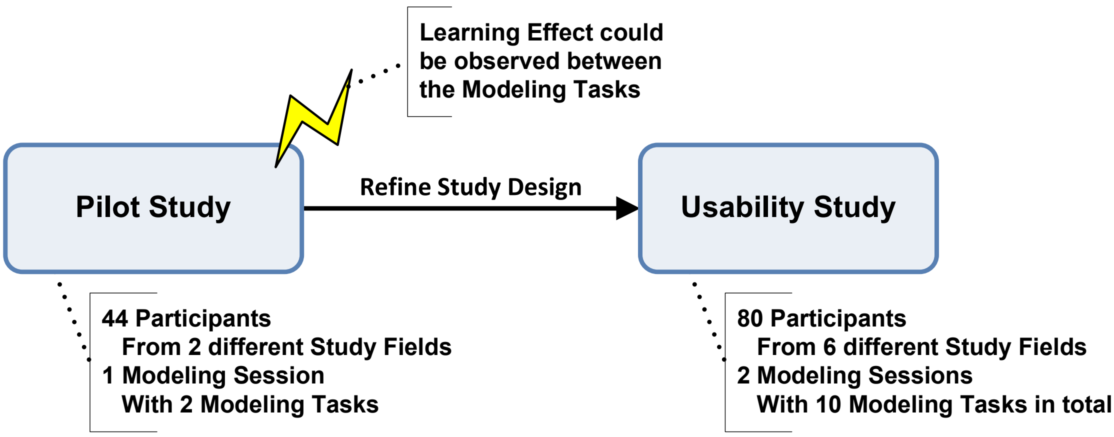


Figure 8.1: Conducted Usability Studies

Fig. 8.1 illustrates the course of the two studies. First, a pilot study was conducted (cf. Section 8.1) in order to assess specific performance measures when working with the developed configurator. When analyzing the results, a *learning effect* could be observed.

In order to focus on investigating this effect, a large-scale study with a more elaborated study design was conducted (cf. Section 8.2).

8.1 Pilot Study

A pilot study assessing the *usability* of the developed QuestionSys configurator was conducted with 44 participants [118]. The following *research question*, including several hypotheses, was defined in concordance with the *Goal Question Metric* [5]:

Goal Question Metric

Research Question

Do end-users understand the modeling concept of the QuestionSys configurator with respect to the complexity of the provided application?

Participants were recruited from various departments at Ulm University and were classified into *novices* and *experts*, depending on their prior knowledge in *process modeling*, which is a fundamental pillar of the QuestionSys approach. During the study, participants had to model two data collection instruments by only using the provided configurator. The *time* and *operations* needed to complete the tasks were assessed automatically, whereas *errors* were assessed manually.

Although the obtained results were quite promising with respect to the assessed performance measures, only one hypothesis could be statistically confirmed. However, the hypotheses stating that *experts* are *faster* and make *less errors* than *novices* could not be statistically proven. Furthermore, the conducted pilot study showed limitations with respect to the validity of the results. For example, most of the participants already worked with process models. This may act as confounder when evaluating the mental efforts required for applying the change patterns. It may further affect the categorization of participants into *notices* and *experts*. Furthermore, the process of recruiting participants itself might be subject for discussion.

Besides these limitations interesting findings could be obtained. For example, a *learning effect* was observed when analyzing the results from the *novices* sample. In particular, the number of *errors* decreased from 4 in Task 1 to 1 in Task 2 (cf. Fig. 8.2), whereas the *errors* remained stable for the *experts* sample (cf. Fig. 8.3).

8.2 Usability Study

Learnability

In order to specifically focus on the discovered *learning effect* as well as to cope with the limitations of the pilot study (cf. Section 8.1), another usability study was conducted. On one hand, the already promising results indicated by the pilot study should be replicated, whereas additional research questions should be addressed on the other. Based on the

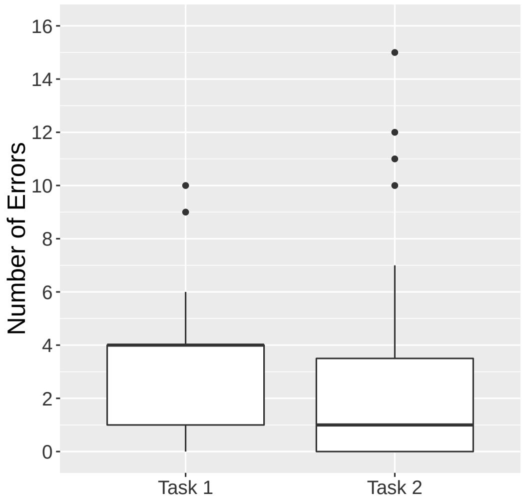


Figure 8.2: Number of Errors (Novices)

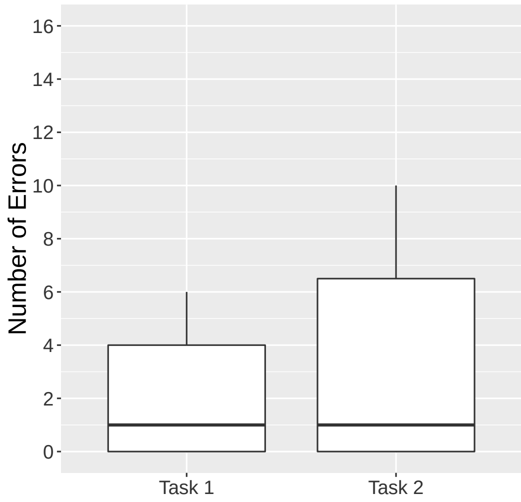


Figure 8.3: Number of Errors (Experts)

gained insights, a larger study with an improved and a more sophisticated study design was conducted. More precisely, participants had to model 10 data collection instruments with the QuestionSys configurator across 2 modeling sessions. In particular, the following research questions were addressed by conducting this large-scale study [119]:

Research Questions

RQ 1: How are the performances of novices and the performances of experts changing from the first to the last task (data collection instrument) of Session 1?

RQ 2: How are the performances of novices and the performances of experts changing from the last task (data collection instrument) of Session 1 to the first task (data collection instrument) of Session 2?

RQ 3: How are the performances of novices and the performances of experts changing from the first to the last task (data collection instrument) of Session 2?

RQ 4: How are the performances of novices and the performances of experts changing from the first task (data collection instrument) of Session 1 to the last task (data collection instrument) of Session 2?

RQ 5: How many tasks (data collection instruments) are necessary until the performance metrics of novices are as good as the performance metrics of experts at the first task (data collection instrument)?

RQ 6: How does the self-reported mental effort change when modeling several data collection instruments?

RQ 7: How are the performance measures of novices and experts compared to the self-reported mental effort at each data collection instrument?

RQ 8: How are the performance measures of novices and experts compared to the self-reported mental effort across all data collection instruments?

RQ 9: How are performance measures of novices and experts compared to the perceived complexity of each data collection instrument?

RQ 10: How are performance measures of novices compared to the perceived complexity across all data collection instruments?

RQ 11: How are performance measures of experts compared to the perceived complexity across all data collection instruments?

8.2.1 Methods

For this study, a more complex procedure, compared to the pilot study, was designed. Recruited participants had to model 10 data collection instruments over the course of two consecutive sessions at Ulm University, using the provided QuestionSys configurator.

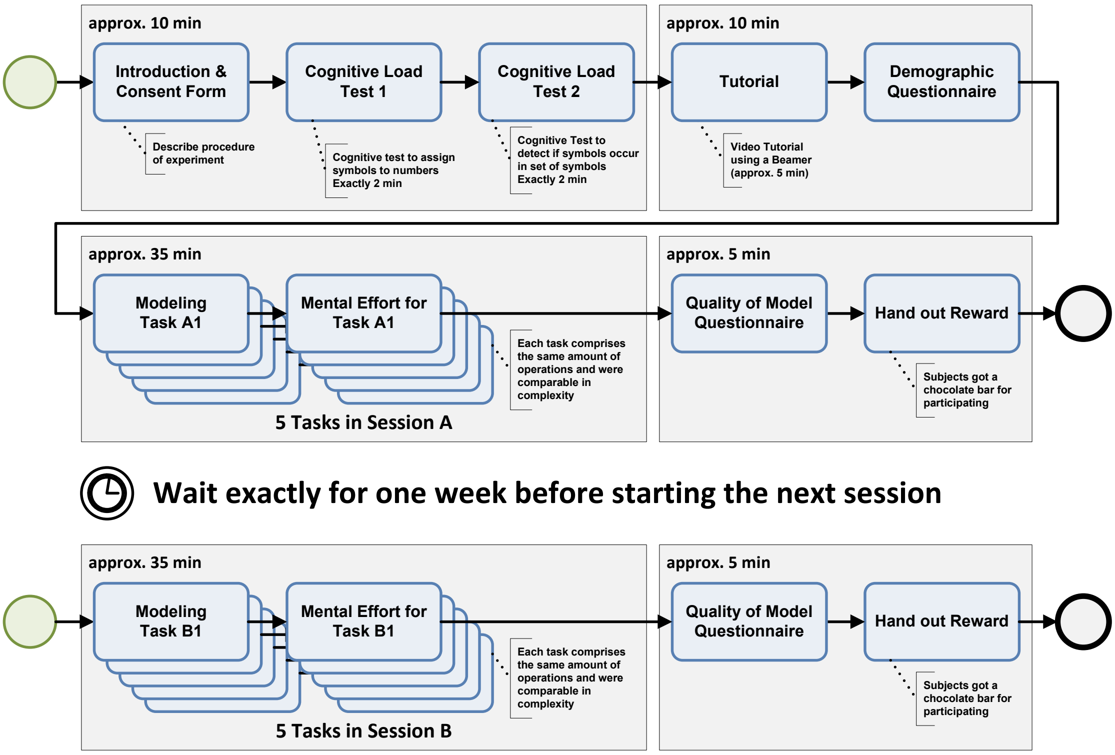


Figure 8.4: Study Design

Fig. 8.4 illustrates the overall study design: participants were informed about the study and had to process two tests measuring their *cognitive load* when working under stress. Before collecting demographic data, a screencast introducing the QuestionSys configurator was presented. For the first study session, participants were asked to solve five tasks (i.e., model data collection instruments). After modeling each instrument, they had to go through a short questionnaire collecting data on mental effort and perceived complexity when working on the respective task. Finally, participants had to go through one last questionnaire asking details on the overall quality of the modeled instruments. Altogether, the first session took about 50 to 60 minutes in total, depending on the participants speed.

Session 2 started exactly one week later. Demographic questions and the screencast were skipped, resulting in a shorter duration of the session (i.e., approximately 30 to 40 minutes in total) compared to the first one. Participants had to process five additional tasks and fill in related questionnaires capturing their mental efforts. Finally, feedback on the quality of their modeled instruments was requested.

Participants

For the study, 80 participants – mainly students and research associates – from different departments (e.g., Computer Science, Economics, Chemistry, Psychology, Medicine) at Ulm University were recruited. It was ensured that the number of female and male participants were almost equal. Then, the participants were ① instructed to adhere to the study design and ② informed about the need to pass two consecutive sessions in order to successfully complete the study. All materials (e.g., task descriptions, consent form, questionnaires) were provided in German [130]. According to the study design, participants who answered the question *"Do you have experience in process modeling?"* with *yes* were classified as *experts*. On the other, participants who answered this question with *no* were classified as *novices* for the subsequent analysis. Altogether, this resulted in 45 novices and 35 experts (80 in total). Note that only 3 out of the 80 participants did not show up for Session 2 (one novice and two experts). Research questions that require data from Session 2, therefore, were investigated with 77 participants (44 novices and 33 experts) instead of 80 (45 novices and 35 experts).

Performance Measures

For the study, the QuestionSys configurator was enhanced with a *Study Mode* enabling specific features. *Performance measures* were automatically assessed. When participants started or completed modeling a data collection instrument, the current *time* (i.e., timestamp) was logged to an Excel file. Furthermore, when editing the instrument (e.g., adding a page) the currently applied *operation* and *timestamp* were logged as well. Finally, after each modeling step (i.e., operation) an image of the current state of the model was generated and stored, which enabled the (manual) assessment of *errors* of the modeled instruments.

To detect differences in the cognitive abilities of both groups (i.e., *experts* and *novices*) two established tests measuring processing speed were performed [125]. Participants were given 2 minutes for each test to assign symbols to numbers ("Digital-Symbol-Coding") and to detect symbols in a set of symbols ("Symbol Search"). Noticeable differences in their cognitive abilities may be a confounder for the conducted study as a higher cognitive ability could result in better / faster *learnability* of the QuestionSys configurator.

All data that was collected in this study is available in [119].

Tasks

All 10 tasks that needed to be processed were comparable regarding their complexity. Note that a difference in the complexity of the models might limit the validity of the obtained results. A change of assessed performance measures, in turn, might be attributed to a diverse model complexity or a measurable learning effect. All tasks were designed in the same way. This includes the textual representation handed out to participants as well as the amount of operations needed in the best case.

The data collection instruments to be modeled were selected from various domains in order to evaluate the feasibility and practical applicability in these settings. Appendix A.1 exemplarily shows one task description that was translated from German to English.

Questionnaires

Throughout the study, additional data was collected using traditional paper-based questionnaires. For example, a demographic questionnaire collecting personal information (e.g., gender or education) was handed out to the participants. More specifically, information regarding prior knowledge on *process modeling* was assessed, as this information was used to classify participants into *novices* and *experts*. After modeling an instrument, participants had to answer 5 questions assessing their mental effort. Thereby, a 7 point Likert-scale with respective answers ranging from *"I strongly agree"* (1) to *"I strongly disagree"* (7) with an additional *"neutral"* element (4) was presented. Finally, participants had to answer questions regarding the quality of the modeled instruments.

8.2.2 Discussion

The overall goal of the study was to evaluate whether *end-users* are able to develop data collection instruments when using the QuestionSys configurator. In order to measure their performance, various measures were assessed. The *time* and *operations* needed to complete the tasks were automatically tracked by the configurator. Furthermore, all created models were manually assessed to evaluate potential *errors*. Finally, participants assessed their performance and mental effort required to solve the given tasks by filling in *self-reporting* questionnaires. During each session, a *learning effect* was observed; the *time* and *operations* needed for modeling were decreasing from task to task (`RQ1` & `RQ3`). Across the two sessions the participants increased their overall performance (`RQ4`), i.e., the *errors* in the modeled data collection instruments were decreasing from the 1^{st} to the

10^{th} task. This *learning effect* with respect to *errors*, however, could not be observed for *experts*, as their models contained few errors already in the first task.

After a break of one week (i.e., participants were not using the QuestionSys configurator during this period), the performance measures for *novices* decreased again, whereas the ones of *experts* remained stable (RQ2). This may be explained due to the fact that experts are working with corresponding applications on a *day-to-day* basis. Novices, in turn, need to get reacquainted with the application. Note that novices performed significantly better, regarding the *time* and *operations* needed, from the third task on, compared to experts in the first task (RQ5). Unfortunately, *novices* were unable to catch up regarding the *errors* in their modeled data collection instruments. To enable untrained domain experts to properly create more error-free data collection instruments, it might be necessary to increase the number of training sessions.

When analyzing the questionnaires, the participants had to fill in right after modeling a data collection instrument, further insights could be obtained. RQ6, for example, revealed that the *mental effort* for modeling instruments is decreasing. Furthermore, RQ7 showed a strong correlation between the self-assessed *mental effort* and the performance measures assessed by the QuestionSys configurator for each task. In detail, *novices* showed 19 (out of 30) and *experts* 11 (out of 30) significant correlations. These correlations may be explained due to the fact that *experts* initially rated the *mental effort* for modeling instruments lower than *novices* did. Furthermore, the *experts*' performance was better than the one of *novices*, i.e., experts were faster, required less operations to complete a task, and made less errors. Finally, a lower mental effort significantly correlated with an overall better performance (RQ8). Above all, this could be shown for both groups, whereas the effect is stronger for *novices*. Again, this may be explained due to the fact that *experts* are more likely working on a *day-to-day* basis with similar applications, and, therefore, retain basic expertise.

In addition to the self-rated mental effort, participants had to give feedback on the perceived complexity of the data collection instruments to be modeled. Again, the results showed significant correlations between the perceived complexity and the performance measures. More specifically, *novices* had 14 (out of 30) and *experts* 12 (out of 30) correlations (RQ9). In other words, the more *time* or *operations* the participants needed, or the more *errors* they made, the higher the perceived complexity was rated by them. Regarding RQ10 and RQ11 the overall performance of both groups were compared to their perceived complexity. Results revealed that an increase in the perceived complexity is also associated with a decrease in performance for both groups.

This study shows limitations that need to be discussed properly. First, the process of recruiting participants might affect generalizability as the study mainly involved students and research associates. However, [34] showed that students can act as proper substitutes in empirical research. Second, categorizing the participants only into two groups may be subject for discussion. The categorization solely based on a single *"yes / no"* question may be subject for further investigations. Both aspects could be addressed in another study with a more sophisticated categorization. One could, for example, categorize the participants by directly observing their modeling behavior. However, tests measuring the processing speed of both groups were performed before working with the QuestionSys configurator, indicating similar cognitive abilities. Third, a baseline comparison between the groups show differences regarding gender, education, and their field of study. Some differences (e.g., the field of study) are intended as participants were recruited specifically from various domains to enable comparison. As stated throughout this thesis, the QuestionSys framework targets at domain experts having no knowledge regarding process modeling and mobile application development respectively. In this study, end-users from medicine, psychology or social sciences are involved. Again, tests measuring processing speed indicate similar abilities regarding their cognitive behavior. Fourth, the *experts* sample was smaller than the one with *novices* (35 experts vs. 45 novices), resulting in a weaker statistical power. Fifth, all tasks to be modeled origin from various domains (e.g., healthcare, travel expense, food delivery) to illustrate the applicability of the developed approach in a multitude of application scenarios. It may be subject to discussion, whether some of the instruments to be modeled were more familiar to participants than others. Fortunately, the `RQs` comparing the perceived complexity as well as the mental effort with the automatically assessed performance measures show a strong correlation between those metrics.

Altogether, the study replicates valuable findings from the pilot study [118]. In particular, results confirm that even *novices* were able to properly model data collection instruments. In detail, the recruited participants got significantly better (i.e., needed less *time* and *operations* and made less *errors*), the longer they worked with the QuestionSys configurator. More precisely, a *learning effect* could be noticed within each session and across both sessions. Altogether, the QuestionSys configurator constitutes a feasible approach for enabling domain experts having little or no prior knowledge in process modeling or mobile application development to create data collection applications themselves.

9 Related Studies

Several studies measuring mental efforts during process modeling are described in literature. Common to them is their focus on the process model. In this context, [53] analyzes the *process of process modeling*, whereas the approach described in [15] visualizes different steps a process modeler undertakes when modeling (business) processes. Moreover, [126] applies eye tracking software to gain a better understanding of factors that may influence the way process models are specified by individuals. Furthermore, [135] presents insights into and lessons learned in studies on process model comprehension that rely on eye tracking studies. In the studies described in Chapter 8, data collection instruments are technically represented by process models. Additional aspects have to be modeled by domain experts, which are irrelevant in the context of process modeling, like the ability to support different languages, element versions, or modes of an instrument (i.e., self-rating vs. interview mode). These aspects might increase the overall mental effort for untrained domain experts when working with a configurator like QuestionSys. Consequently, the studies described in Chapter 8 differ from the above ones.

Process Modeling

Psychological studies revealed manifold insights into the measurement of *mental efforts*. For example, [122] introduces the *Cognitive Load Theory* that provides guidelines to assist learners to actively process available information as working memory capacity is limited. Closely related, [56] presents concepts on how to effectively measure mental effort when working on specific tasks. Additional ideas on how to derive conclusions with respect to individuals are proposed. The approach described in [61] focuses on educational perspectives and discusses the *process of learning* more generally. Finally, [124] summarizes related challenges and discusses potential research directions. Related to the studies presented in Chapter 8, [134] describes an eye tracking study measuring

Mental Effort

Cognitive Load Theory

the mental effort of participants when modeling (business) processes. [134] showed that the mental effort for modeling tasks quickly reaches cognitive limitations thwarting the performance of experts and novices in modeling.

End-User Programming

End-User Programming approaches have proven their feasibility in a multitude of studies. In particular, they shall support non-programmers in *developing* software applications. For example, [36] provides an environment allowing system administrators to visually model script-based applications. An experiment investigated the practical applicability of the proposed approach. In turn, [6] introduced a graphical programming language, representing each function of a computer program as a block. Blocks, in turn, may be built upon each other to (graphically) develop a software application.

Domain-Specific Configurator

In the field of *domain-specific configurators* for developing, configuring, and maintaining software applications, only few evaluations have been reported in literature. For example, [3] compared a web-based configurator for *ambulatory assessments* against *movisensXS*, which is a commercial solution for Ecological Momentary Assessments. The authors evaluated their configurator with two experts on one hand. On the other, 10 participants evaluated the respective client application for enacting the configured assessment. Both parts of the study rely on standardized user-experience questionnaires (e.g., *SUS* [9]) to collect feedback from individuals working with the application. Compared to the studies presented in this thesis, the results are limited due to the low number of participants. Furthermore, only self-rated user perception has been considered as a metric for the usability of the application, completely ignoring automatically collected performance measures.

System Usability Scale

A web-based configurator to create and coordinate experiments in the context of information retrieval is presented in [80]. In particular, the authors evaluated the application they have developed in two ways: The backend management system was evaluated by one researcher focusing on *human-computer interaction* and by one regular student. Both participants confirmed a good usability. The frontend, however, was evaluated with a study comprising 48 participants. Comparable to the studies presented in this thesis, the application tracked the time to complete respective tasks. Furthermore, participants were asked to provide feedback with respect to their performance. Compared to these studies, the studies presented in Chapter 8 pursued different approaches. More specifically, the QuestionSys configurator was evaluated along observable correctness properties of the modeled instruments. Following this approach, performance measures (e.g., the time to complete a model or the operations needed) were automatically assessed and evaluated over a certain period of time. Finally, the performance measures were compared with the self-reported mental effort of participants when modeling respective instruments.

Learnability

In conclusion, the conducted studies specifically focused on measuring the *learnability* of the QuestionSys configurator. This approach may be considered as a promising way to evaluate the usability of applications in general. Measuring learnability, however, is a time-consuming endeavor. In more detail, *learning* is often considered as a process over time, taking practical experience into account as well. When measuring learnability, this means that a consecutive series of tasks need to be executed over a certain period of time and corresponding performance measures need to be assessed. Due to the time-consuming procedure of measuring learnability, however, such studies are often neglected [133]. Learnability, however, might have an impact on the success or failure of an application in real-world scenarios [28]. In order to ensure usability, more effort is put into the evaluation of best practices for creating a *user-friendly* software application. Mostly, the design of the *user interface* [47, 54, 120] or overall *user experience* [30, 48] are considered. Although standardized self-report questionnaires (e.g., common usability scales, like SUS) may assess respective properties fairly easy, they might be misleading when evaluating sophisticated applications like the QuestionSys configurator.

Part IV

Conclusion

10 Summary and Outlook

To mitigate the limitations of paper-based instruments, digital solutions based on common Web technologies were established. However, most solutions are unable to cope with the demanding requirements of many large-scale data collection scenarios like the use of *sensors* to collect vital parameters during interviews or the *offline processing* of instruments (i.e., if no stable Internet connection is available). *Smart mobile devices* (i.e., smartphones or tablets), have the potential to close this gap and to meet these complex requirements.

Developing mobile applications for collecting data in large-scale scenarios is a challenging task. For example, the short release cycles from vendors as well as platform-specific peculiarities (e.g., diverging user interfaces) need to be taken into account. Maintaining mobile data collection applications, therefore, is complex, time-consuming, and costly as both domain experts and application developers need to be involved.

The QuestionSys framework describes methods that empower domain experts to develop sophisticated mobile data collection applications themselves, i.e., without need to involve any IT experts. The QuestionSys framework presents a model-driven configurator that applies techniques known from end-user programming to properly support domain experts. Usability studies conducted with untrained participants have shown the practical feasibility of the approach. The instruments modeled with the configurator, in turn, can be deployed to and flexibly executed on smart mobile devices to collect data.

The QuestionSys framework with its model-driven approach will significantly increase the speed for developing mobile data collection applications. Furthermore, it will reduce costs and relieve application developers from manual tasks, like migrating existing applications to new operating system versions. Moreover, the communication overhead between domain experts and application developers will be significantly reduced as domain experts are empowered to digitize instruments themselves. Finally, the developed approach demonstrates the applicability of process management techniques in a broader scope compared to business process support.

10.1 Contribution

QuestionSys Framework

The thesis presents the *QuestionSys framework* that empowers domain experts to create data collection instruments. In a multitude of interviews conducted with experts from various domains, fundamental requirements for realizing data collection scenarios were elaborated. In this thesis, a generic concept was developed serving a multitude of application scenarios from various domains. Fig. 10.1 summarizes core contributions of the thesis.

Configurator

For developing complex data collection instruments, QuestionSys provides a model-driven *configurator*. The latter applies *process management* technologies in a broader scope by mapping instruments to executable process models. The mapping allows specifying the flow of an instrument on an abstract, i.e., platform-independent, level. Note that QuestionSys applies techniques known from *end-user programming*.

Usability Study

Usability studies showed that participants were able to properly use the configurator. First, a pilot study revealed a *learning effect* from modeling task to modeling task. Second, to investigate this effect, a more complex study was designed, which reproduced valuable insights from the pilot study and enabled additional insights into the process of modeling instruments. In particular, it was shown that participants were able to properly use the configurator, i.e., the *mental effort* for modeling data collection instruments with the QuestionSys configurator continuously decreased from task to task. In this context, not only self-reported mental effort was evaluated, but also performance measures like the *time* and *operations* needed to complete specific tasks. Overall, the values were decreasing over time, indicating a promising approach for domain experts without knowledge in process modeling or application development in general.

Lightweight Process Engine

Executable Component

The QuestionSys framework enables the deployment of modeled instruments to smart mobile devices (e.g., smartphones or tablets) to collect data with them. For this purpose, a *lightweight mobile process engine* was developed that is capable of interpreting and executing instruments in a robust and efficient manner. To enable the later extension of the mobile data collection application, *Executable Components* were introduced. These components, in turn, provide the logic for presenting the user interface or for collecting entered data. Further, they are not part of the lightweight mobile process engine itself, but rather *extend* its functionality. More specifically, the engine communicates with `ECs` like with external services and allows exchanging these components on demand. This allows flexibly adapting the mobile data collection client to new emerging requirements.

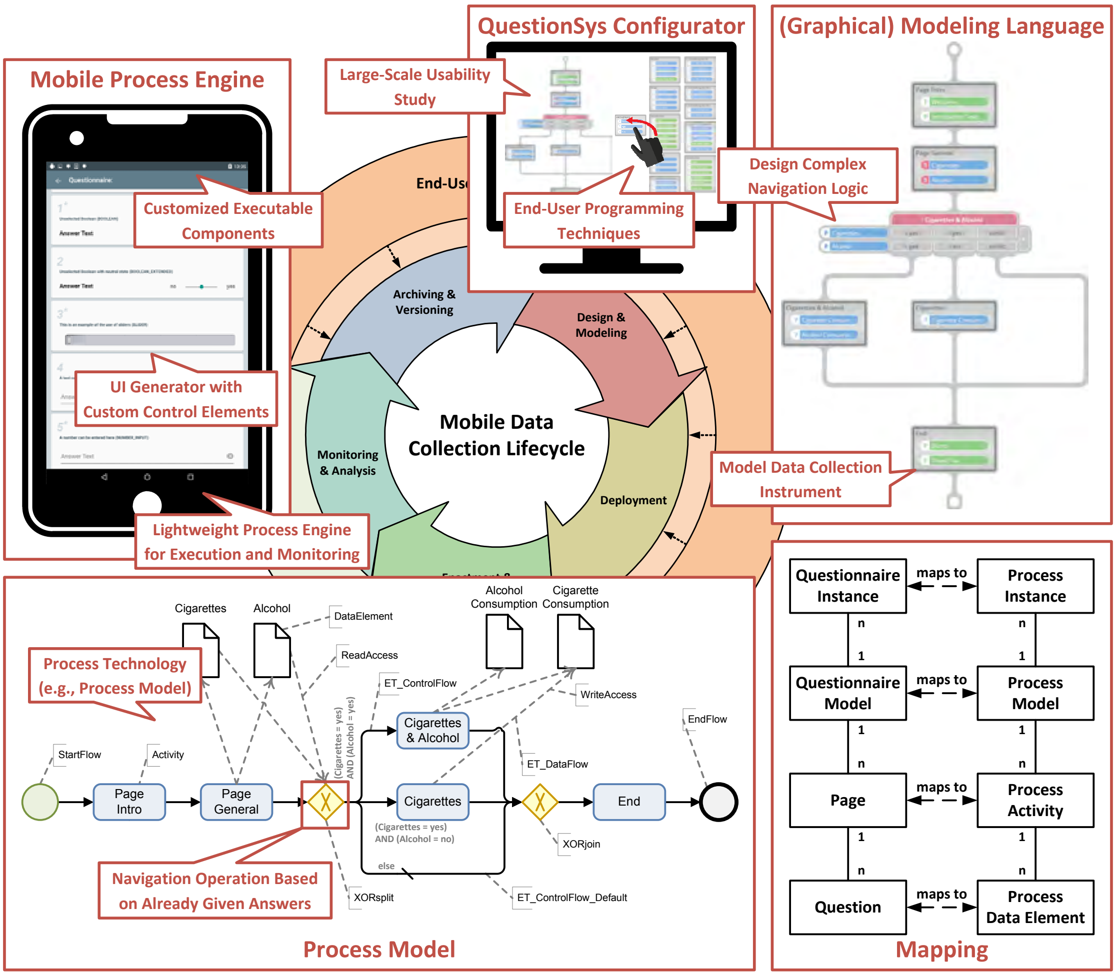


Figure 10.1: QuestionSys Framework

Altogether, the QuestionSys framework has the potential to significantly influence the way mobile data collection applications will be developed in future. First, large-scale data collection scenarios, like clinical trials or psychological studies, will benefit from the short development cycles for mobile instruments. Second, the modeling language used by the configurator might contribute towards a common (graphical) notation and, thus, foster the communication between domain experts and application developers. Finally, QuestionSys can serve as a valuable benchmark for mobile data collection in general. This includes the graphical modeling of instruments as well as their flexible execution on smart mobile devices.

10.2 Additional Publications

In addition to the core publications of this thesis, its author was involved in a number of additional publications related to *data collection applications*.

[35, 83, 105] describe early works dealing with data collection applications in the psychological domain. In detail, psychologists were supported in various scenarios (e.g., collecting data on adverse childhood experience or detecting risky pregnancies) by implementing mobile applications. Note that the requirements gathered from interviews with domain experts as well as the experiences gained during the process of developing and maintaining these applications, triggered the research on the QuestionSys framework. Insights into the related development process were published in [110].

Mobile data collection in the context of mobile crowdsensing applications is introduced in [94]. More specifically, the work presented in [68, 71, 74] focuses on technical details of the *TrackYourTinnitus* platform, whereas [65, 66, 101] present scientific results obtained from the analysis of the data collected with this data collection application.

In [106], a sophisticated *sensor framework* is presented that allows connecting sensors to smart mobile devices. The framework provides features to retrieve data from internal sensors (e.g., camera or microphone) as well as external ones (e.g., pulse sensor connected via `Bluetooth`). Corresponding data can be both analyzed and visualized in order to provide additional information during data collection in clinical trials.

Insights into the development and maintenance of mobile applications were reported in [93].

10.3 Outlook

Properly supporting end-users in collecting data in large-scale application scenarios, like clinical trials, is a complex endeavor, which can be only partially covered by a thesis. The latter revealed several aspects that are not part of this manuscript, but may be addressed in future research:

Process Management

- The integration of QuestionSys with concepts, methods and technologies known from the field of (business) *process management* offers promising perspectives and, hence, should be investigated in future work as well. For example, the management of instruments may adopt concepts like process configuration [2, 27], process compliance checking and monitoring [40, 50], context-aware process injection [57], and process schema evolution [82].

Process Mining

- *Process mining* algorithms [123] may be applied to discover additional insights into the execution of mobile processes, i.e., data collection instruments running on smart mobile devices. The benefits of corresponding approaches are described in [51], which applied existing process mining algorithms to evaluate selected hospital processes. More specifically, the control flow perspective (i.e., *"Are processes executed exactly as they were specified or do they deviate from the specified behavior?"*), the organizational perspective (i.e., *"Which participants are involved in this process and with whom do they work together?"*), and the performance perspective (i.e., *"What is the execution time for specific cases and which participants did work on the latter?"*) were evaluated and visualized.

- In the current version of the QuestionSys configurator, the integration of *sensors* into data collection instruments is limited. Although smart mobile devices offer plenty of *internal sensors*, the mobile data collection application currently focuses on the most common ones (e.g., microphone or camera). However, *external sensors*, connected via `Bluetooth` or `WLAN`, need to be explicitly integrated by implementing respective code. Note that this is aggravated due to the fact that in most cases the vendors of such sensors do not offer public APIs to communicate with corresponding devices. For this purpose, the QuestionSys configurator provides a generic element that allows specifying sensor configurations. A corresponding mobile data collection application, or rather the *`EC`* being responsible for handling the logic to interact with the sensor, need to properly interpret and handle this configuration. Though the used JSON configuration objects constitute a rather pragmatic approach, it is not suitable for domain experts. In consequence, *end-user programming* techniques should be applied as well. *Sensors*

- When realizing mobile data collection applications novel control elements for entering data were introduced and evaluated in usability studies. More specifically, these elements were compared to common ones known from other mobile applications. Results indicate that some of the new control elements were well understood by the users interacting with a created mobile application, i.e., the elements were rated positively in respect to usability aspects. Similar to the *study* measuring *learnability* of the configurator, another study should measure the performance of participants when processing an instrument, i.e., entering data. Especially, the newly introduced control elements may enable a faster processing of instruments. Likewise, an additional study on modeling sensors should evaluate whether or not domain experts are able to properly use this feature in their data collection instruments. *Usability Study*

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Index

Acronyms

ADEPT Application Development Based on Pre-Modeled Process Templates

API Application Programming Interface

BPEL Business Process Execution Language

BPM Business Process Management

BPMN Business Process Modeling and Notation

CLT Cognitive Load Theory

CSS Cascading Style Sheets

DHTML Dynamic HTML

DSL Domain-Specific Language

EC Executable Component

EMA Ecological Momentary Assessment

EPC Event-driven Process Chain

ESM Experience Sampling Method

EUD End-User Development

EUP End-User Programming

GPS Global Positioning System

GQM Goal Question Metric

HTML Hypertext Markup Language

JSON JavaScript Object Notation

MDC Mobile Data Collection

MDD Model-Driven Development

PAIS Process-Aware Information System

PTSD Post-Traumatic Stress Disorder

REST Representational State Transfer

SMS Short Message Service

SQL Structured Query Language

SUS System Usability Scale

UML Unified Modeling Language

WS Web Service

WYSIWYG What You See Is What You Get

XML Extensible Markup Language

Part V

Appendix

A
Appendix Files

A.1 Example Modeling Task Description

Task: Patient Information Questionnaire

In this task you should model a questionnaire asking for information needed in the context of a medical intervention (e.g., a gastroscopy) and educate the patient about possible risks.

Carefully read the text before starting modeling. If you have read the task to be modeled, please start the **QuestionSys configurator** application via the provided shortcut on your desktop.

Select the following workspace:

Workspace:	**Study**
Questionnaire:	**Patient Information**

Open the "**Editor**" view and start modeling the respective questionnaire. Save the final model to the desktop of your computer.

1. The first page of the questionnaire contains a headline and text element with general information regarding the upcoming medical intervention (e.g., gastroscopy). Furthermore, demographic information of the patient (e.g., name, age, gender, …) shall be collected. Additionally, the patient should answer, whether a family member shall be contacted after the intervention. If "yes", the patient shall continue with page 2, otherwise with page 3.
2. The second page shall only be displayed if the patient wants a family member to be informed regarding the course of the intervention. This page shall ask about details of the person to be informed (e.g., name, phone number, …).
3. Regardless of whether one should be informed, the 3rd page will be displayed next. This page contains a text if the patient wishes to be anesthetized or not. Thereby, the following options may be available: none, local, full.
4. This page, in turn, shall only be displayed if the intervention takes place under local anesthesia. Thereby, an additional form shall be displayed to provide information regarding possible risks. The patient has to sign this form in order to continue.
5. This page, in turn, shall only be displayed if the intervention takes place under full anesthesia. It shall display similar information as described before, however, texts shall be adapted in order to reflect the given circumstances.

This task description was originally provided in German and was translated to English for the publication J. Schobel, R. Pryss, T. Probst, W. Schlee, M. Schickler, and M. Reichert. Learnability of a Configurator Empowering End Users to Create Mobile Data Collection Instruments: Usability Study. JMIR mHealth and uHealth, *6(6):e148, 2018*

Mental Effort: Patient Information Questionnaire

Answer the following questions:

1. The mental effort for creating the model was considerably high.

strongly agree	agree	rather agree	neutral	rather disagree	disagree	strongly disagree
○	○	○	○	○	○	○

2. I was able to properly solve the given task.

strongly agree	agree	rather agree	neutral	rather disagree	disagree	strongly disagree
○	○	○	○	○	○	○

3. The task was rather difficult.

strongly agree	agree	rather agree	neutral	rather disagree	disagree	strongly disagree
○	○	○	○	○	○	○

4. I had to concentrate myself when creating the model.

strongly agree	agree	rather agree	neutral	rather disagree	disagree	strongly disagree
○	○	○	○	○	○	○

5. Creating the model was exhausting.

strongly agree	agree	rather agree	neutral	rather disagree	disagree	strongly disagree
○	○	○	○	○	○	○

This task description was originally provided in German and was translated to English for the publication J. Schobel, R. Pryss, T. Probst, W. Schlee, M. Schickler, and M. Reichert. Learnability of a Configurator Empowering End Users to Create Mobile Data Collection Instruments: Usability Study. JMIR mHealth and uHealth, *6(6):e148, 2018*

B
List of Publications

This appendix contains all publications that are part of this Ph. D. thesis.

SPWSR16 J. Schobel, R. Pryss, W. Wipp, M. Schickler, and M. Reichert. A Mobile Service Engine Enabling Complex Data Collection Applications. In *14th Int'l Conf on Service Oriented Computing (ICSOC)*, number 9936 in LNCS, pages 626–633, October 2016 97

SPSRER16 J. Schobel, R. Pryss, M. Schickler, M. Ruf-Leuschner, T. Elbert, and M. Reichert. End-User Programming of Mobile Services: Empowering Domain Experts to Implement Mobile Data Collection Applications. In *5th IEEE Int'l Conf on Mobile Services (MS)*, pages 1–8. IEEE Computer Society Press, May 2016 98

SPSR17a J. Schobel, R. Pryss, M. Schickler, and M. Reichert. Towards Patterns for Defining and Changing Data Collection Instruments in Mobile Healthcare Scenarios. In *30th IEEE Int'l Symp on Computer-Based Medical Systems (CBMS)*, June 2017 98

SPSPGSR17 J. Schobel, R. Pryss, W. Schlee, T. Probst, D. Gebhardt, M. Schickler, and M. Reichert. Development of Mobile Data Collection Applications by Domain Experts: Experimental Results from a Usability Study. In *29th Int'l Conf on Advanced Information Systems Engineering (CAiSE)*, number 10253 in LNCS, pages 60–75. Springer, June 2017 99

SPPSSR18 J. Schobel, R. Pryss, T. Probst, W. Schlee, M. Schickler, and M. Reichert. Learnability of a Configurator Empowering End Users to Create Mobile Data Collection Instruments: Usability Study. *JMIR mHealth and uHealth*, 6(6):e148, 2018 99

B.1 Using Smart Mobile Devices for Collecting Structured Data in Clinical Trials: Results From a Large-Scale Case Study

The following article was published as follows:

J. Schobel, R. Pryss, and M. Reichert. Using Smart Mobile Devices for Collecting Structured Data in Clinical Trials: Results From a Large-Scale Case Study. In *28th IEEE Int'l Symp on Computer-Based Medical Systems (CBMS)*, pages 13–18. IEEE Computer Society Press, June 2015

The original article is available at:
https://ieeexplore.ieee.org/document/7167446/

B.2 Process-Driven Data Collection with Smart Mobile Devices

The following article was published as follows:

J. Schobel, M. Schickler, R. Pryss, and M. Reichert. Process-Driven Data Collection with Smart Mobile Devices. In *10th Int'l Conf on Web Information Systems and Technologies (Revised Selected Papers)*, number 226 in LNBIP, pages 347–362. Springer, 2015

The original article is available at:
https://link.springer.com/chapter/10.1007/978-3-319-27030-2_22

B.3 A Lightweight Process Engine for Enabling Advanced Mobile Applications

The following article was published as follows:

J. Schobel, R. Pryss, M. Schickler, and M. Reichert. A Lightweight Process Engine for Enabling Advanced Mobile Applications. In *24th Int'l Conf on Cooperative Information Systems (CoopIS)*, number 10033 in LNCS, pages 552–569. Springer, October 2016

The original article is available at:
https://link.springer.com/chapter/10.1007/978-3-319-48472-3_33

B.4 A Configurator Component for End-User Defined Mobile Data Collection Processes

The following article was published as follows:

J. Schobel, R. Pryss, M. Schickler, and M. Reichert. A Configurator Component for End-User Defined Mobile Data Collection Processes. In *Demo Track of the 14th Int'l Conf on Service Oriented Computing (ICSOC)*, October 2016

The original article is available at:
https://link.springer.com/chapter/10.1007/978-3-319-68136-8_28

B.5 Towards Flexible Mobile Data Collection in Healthcare

The following article was published as follows:

J. Schobel, R. Pryss, M. Schickler, and M. Reichert. Towards Flexible Mobile Data Collection in Healthcare. In *29th IEEE Int'l Symp on Computer-Based Medical Systems (CBMS)*, pages 181–182, June 2016

The original article is available at:
https://ieeexplore.ieee.org/document/7545980/

B.6 A Mobile Service Engine Enabling Complex Data Collection Applications

The following article was published as follows:

J. Schobel, R. Pryss, W. Wipp, M. Schickler, and M. Reichert. A Mobile Service Engine Enabling Complex Data Collection Applications. In *14th Int'l Conf on Service Oriented Computing (ICSOC)*, number 9936 in LNCS, pages 626–633, October 2016

The original article is available at:
https://link.springer.com/chapter/10.1007/978-3-319-46295-0_42

B.7 End-User Programming of Mobile Services: Empowering Domain Experts to Implement Mobile Data Collection Applications

The following article was published as follows:

J. Schobel, R. Pryss, M. Schickler, M. Ruf-Leuschner, T. Elbert, and M. Reichert. End-User Programming of Mobile Services: Empowering Domain Experts to Implement Mobile Data Collection Applications. In *5th IEEE Int'l Conf on Mobile Services (MS)*, pages 1–8. IEEE Computer Society Press, May 2016

The original article is available at:
https://ieeexplore.ieee.org/document/7787028/

B.8 Towards Patterns for Defining and Changing Data Collection Instruments in Mobile Healthcare Scenarios

The following article was published as follows:

J. Schobel, R. Pryss, M. Schickler, and M. Reichert. Towards Patterns for Defining and Changing Data Collection Instruments in Mobile Healthcare Scenarios. In *30th IEEE Int'l Symp on Computer-Based Medical Systems (CBMS)*, June 2017

The original article is available at:
https://ieeexplore.ieee.org/document/8104165/

B.9 Development of Mobile Data Collection Applications by Domain Experts: Experimental Results from a Usability Study

The following article was published as follows:

J. Schobel, R. Pryss, W. Schlee, T. Probst, D. Gebhardt, M. Schickler, and M. Reichert. Development of Mobile Data Collection Applications by Domain Experts: Experimental Results from a Usability Study. In *29th Int'l Conf on Advanced Information Systems Engineering (CAiSE)*, number 10253 in LNCS, pages 60–75. Springer, June 2017

The original article is available at:
https://link.springer.com/chapter/10.1007/978-3-319-59536-8_5

B.10 Learnability of a Configurator Empowering End Users to Create Mobile Data Collection Instruments: Usability Study

The following article was published as follows:

J. Schobel, R. Pryss, T. Probst, W. Schlee, M. Schickler, and M. Reichert. Learnability of a Configurator Empowering End Users to Create Mobile Data Collection Instruments: Usability Study. *JMIR mHealth and uHealth*, 6(6):e148, 2018

The original article is available at:
https://mhealth.jmir.org/2018/6/e148

C
Complete List of Publications

The following is the complete list of publications the author of this Ph. D. thesis has been involved in.

Peer-Reviewed Journals

2016

- R. Pryss, P. Geiger, M. Schickler, J. Schobel, and M. Reichert. Advanced Algorithms for Location-Based Smart Mobile Augmented Reality Applications. *Procedia Computer Science*, 94:97–104, 2016
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D
Discussion of Personal Contribution

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The contribution of the individual authors for respective publications that are part of this Ph. D. thesis are discussed in the following:

D.1 Using Smart Mobile Devices for Collecting Structured Data in Clinical Trials: Results From a Large-Scale Case Study

The author of this Ph. D. thesis was responsible for assessing the requirements in the context of the presented mobile application to assist researchers in collecting data in their psychological trials. In this context, requirement analysis, coordination of the development process as well as the deployment was supervised by the Ph. D. candidate. Dr. Pryss advised the candidate in the development of a proper strategy for dealing with such long-running projects. Both, Dr. Pryss and Prof. Reichert provided assistance in proof-reading the draft of the manuscript.

D.2 Process-Driven Data Collection with Smart Mobile Devices

The author of this Ph. D. thesis was responsible for conducting interviews with experts from various domains in order to document requirements. In this context, Dr. Pryss gave valuable suggestions on how to properly structure respective interviews. The candidate developed a mental model that allows for mapping an instrument to a process model. Both Prof. Reichert and Dr. Pryss suggested improvements for the developed model. The Ph. D. candidate developed a first prototype application using this mental model. All authors helped proof-reading the manuscript.

D.3 A Lightweight Process Engine for Enabling Advanced Mobile Applications

The Ph. D. candidate was responsible for developing the theoretical architecture of the lightweight process engine running on smart mobile devices. In this context, various modules have been designed by the candidate. Moreover, the concept of using Executable Components that are controlled and coordinated by the process engine was developed by the Ph. D. candidate. Further, a concept of automatically evaluating the collected data based on rules were drafted and realized by the candidate. Dr. Pryss assisted the Ph. D. candidate with designing the software architecture for the mobile process engine and its data analysis component. All authors drafted and helped proof-reading the manuscript.

D.4 A Configurator Component for End-User Defined Mobile Data Collection Processes

The Ph. D. candidate was responsible for implementing respective configurator component of the QuestionSys framework. Dr. Pryss and Mr. Schickler, in turn, helped the candidate to develop the architecture of the framework on a conceptual level in numerous meetings. All authors helped proof-reading the manuscript and gave feedback.

D.5 Towards Flexible Mobile Data Collection in Healthcare

The Ph. D. candidate defined flexibility aspects along different phases of data collection scenarios. In this context, techniques enabling flexibility in various realized mobile data collection applications were assessed by the candidate. Dr. Pryss advises the candidate to further refine and properly classify the discovered techniques. All authors drafted and revised the publication.

D.6 A Mobile Service Engine Enabling Complex Data Collection Applications

The Ph. D. candidate was responsible for developing the theoretical architecture of the lightweight process engine running on smart mobile devices. In this context, various modules have been designed by the candidate. Moreover, the concept of using Executable Components that are controlled and coordinated by the process engine was developed by the Ph. D. candidate. Further, he assisted and supervised Mr. Wipp, who developed the proof-of-concept implementation. Dr. Pryss assisted the Ph. D. candidate with designing the software architecture for the mobile process engine. All authors drafted and helped proof-reading the manuscript.

D.7 End-User Programming of Mobile Services: Empowering Domain Experts to Implement Mobile Data Collection Applications

The Ph. D. candidate was responsible for developing a sophisticated lifecycle comprising common phases of various data collection scenarios. Most of these scenarios, in turn, were supported by the candidate by either implementing mobile data collection applications or providing management assistance and guidance in order to properly realize such real-world scenarios. Dr. Ruf-Leuschner and Prof. Elbert helped by providing sophisticated insights into various psychological studies and assisted the candidate in elaborating domain specific requirements. Dr. Pryss and Mr. Schickler, in turn, helped the candidate to develop the architecture of the framework on a conceptual level in numerous meetings. The Ph. D. candidate implemented the prototypes of the QuestionSys framework. All authors helped proof-reading the manuscript and gave feedback.

D.8 Towards Patterns for Defining and Changing Data Collection Instruments in Mobile Healthcare Scenarios

The author of this Ph. D. thesis was responsible for creating an initial list of patterns allowing for adapting data collection instruments. Moreover, these patterns were extracted by the candidate by evaluating various realized mobile data collection applications. Dr. Pryss advised the candidate in classifying the identified patterns and applying a proper scientific methodology with respect to their validation. All authors were responsible for refining the initial list of patterns as well as proof-reading the manuscript.

D.9 Development of Mobile Data Collection Applications by Domain Experts: Experimental Results from a Usability Study

The Ph. D. candidate was responsible for implementing the required features for the configurator component in order to assess performance measures of participants. Dr. Schlee advised the candidate with respect to the study design, whereas Mr. Gebhardt assisted the candidate during the study procedure and helped collecting data from recruited participants. Prof. Probst helped with analyzing the collected data and interpreting the results. Dr. Pryss helped with writing the first draft of the manuscript, while all authors provided valuable input when proof-reading the manuscript.

D.10 Learnability of a Configurator Empowering End Users to Create Mobile Data Collection Instruments: Usability Study

The author of this Ph. D. thesis was responsible for developing the required features in order to automatically assess performance measures of participants. Further, the candidate manually assessed all modeled data collection instruments in order to determine the errors made by respective participants. Dr. Schlee and Prof. Probst advised the Ph. D. candidate in designing the study and helped with analyzing the collected experiment data. Dr. Pryss and Prof. Probst helped with writing the first draft of the manuscript, whereas all authors gave valuable feedback when proof-reading the article.

E
Curriculum Vitae

Curriculum Vitae

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Name:	Johannes Schobel
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Scientific Education

02/2012 – 09/2018 **Ph. D. Thesis**
Institute of Databases and Information Systems, Ulm University, Ulm
- Title: "A Model-Driven Framework for Enabling Flexible and Robust Mobile Data Collection Applications"

04/2009 – 01/2012 **Studies in Computer Science**
Ulm University, Ulm
- Grade: Master of Computer Science
- Degree: M.Sc.
- Master's Thesis: "Business Process Intelligence: Aktueller Stand und neue innovative Ansätze zur intelligenten Prozessanalyse"

10/2005 – 03/2009 **Studies in Computer Science**
Ulm University, Ulm
- Grade: Bachelor of Computer Science
- Degree: B.Sc.

09/2000 – 06/2005 **Higher School Graduation**
Höhere Technische Bundes- Lehr- und Versuchsanstalt (HTL), Dornbirn
- Grade: Matura

09/1996 – 07/2000 **Higher School Graduation**
Gymnasium Gallusstraße, Bregenz

09/1992 – 07/1996 **Elemantary School**
Volksschule, Höchst