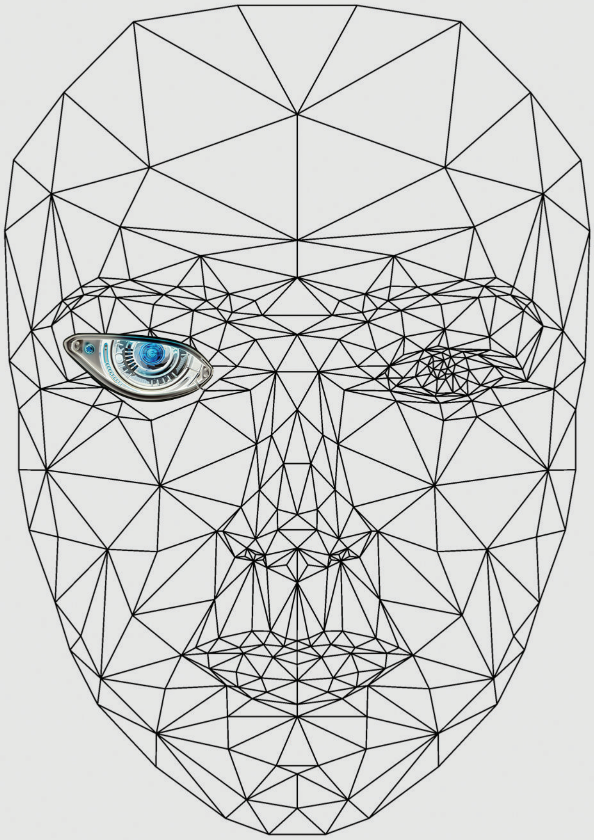

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Software Quality Management in Industry 4.0 & Autonomous Driving

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SOFTWARE QUALITY MANAGEMENT

IN

INDUSTRY 4.0 &
AUTONOMOUS DRIVING

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List of abbreviations

AD	Autonomous Driving
AI	Artificial Intelligence
ALM	Application Life cycle Management
AV	Autonomous Vehicle
BMI	Brain-Machine Interface
CD	Continuous Delivery
CI	Continuous Integration
CMM	Capability Maturity Model
CMMI	Capability Maturity Model Integration
CPS	Cyber-Physical Systems
CT	Continuous Testing
IEEE	Institute of Electrical and Electronics Engineers
IIoT	Industrial Internet of Things
IoS	Internet of Services
IoT	Internet of Things
IT	Information Technology
MaaS	Mobility-as-a-Service
QA	Quality Assurance
QM	Quality Management
S-SDLC	Secure software development life cycle
SAFe	Scaled Agile Frameworks
SDLC	Software development life cycle
SPI	Software process improvement
SQ	Software quality
SQA	Software quality assurance
SQC	Software quality control
SQM	Software quality management
SQP	Software quality planning
TaaS	Transportation-as-a-Service
TQM	Total Quality Management
UAT	User Acceptance Testing
UI	User Interface

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1. Introduction

1.1 Why SQM isn't popular, but should be

Software is the controlling element of almost every technological innovation since the Digital Revolution, also known as the Third Industrial Revolution.[1] As we're now in the take-off phase of the of the Fourth Industrial Revolution software could even be considered to be the brains of the systems that we build around ourselves. "As we implement smart technologies in our factories and workplaces, connected machines will interact, visualize the entire production chain and make decisions autonomously."[2]
If we expect our human brains to be replaced on a large scale by software automations ("On one estimate, 47% of US jobs are at risk from automation."[3]) it's a given that these software solutions should function correctly, predictably and manageably. People need to trust them and be able to rely on them.
The concerns about software quality (SQ) aren't limited to industries and business, but also extend to our everyday lives. The semi-autonomous driver assistance of Tesla cars drew public attention in the last years because of fatal accidents due to software failures.[4] In another case the sensors of an Autonomous Driving prototype of the company Uber recognized a pedestrian, but the software decided no reaction was needed, which led to a deadly accident.[5] Less drastic but for sure disturbing was the instance at which an Amazon Echo recorded a family's conversation and then sent it to a random person in their contacts.[6] To make this work an understanding of a broader spectrum, another example could be drawn from the best-selling watch.[7] "The [newest] Apple Watch's ECG feature is FDA-cleared to detect atrial fibrillation (an irregular heart rate that increases your risk for stroke and heart failure) and to give users notifications that their heartbeat is irregular. This seems great in theory, but doctors are a little wary."[8] The quality of the software may decide whether lots of healthy people run to the doctor thinking they have an arrhythmia, when in fact they don't. The difference of these examples to other situations, where software failures cause malfunctions, non-usability or instability, is the immediacy how the quality of software becomes a question of business success, health and security.

[1] see Sheninger, E.C., Murray, T.C. (2017), p.15
[2] Marr, B. (2018), URL see references
[3] Elliot, L. (2016), URL see references
[4] see Matousek, M. (2018), URL see references
[5] see Barkhausen, B. (2018), URL see references
[6] see Shaban, H. (2018), URL see references
[7] see Kerkmann, C. (2018), URL see references
[8] Miller, K. (2018), URL see references

The term Industry 4.0 will be discussed in detail in another chapter. But the relevance of new ways of how to manage software quality can be well illustrated by looking at the definition of Industry 4.0 by Hainer Lasi et al. In their publication from 2014 the authors mention general social, economic, and political changes. In particular, short development periods, individualization on demand, flexibility, decentralization and resource efficiency are summarized as pull of demand.[9] This allocation of non-deterministic and non-linear characteristics has also led to agile concepts in software development.

Agile methods, which will also be discussed in detail later, have dominated software engineering in the second half of the past 50 years.[10] "The fundamental problem with testing in an .. Agile environment is that, since there are generally no standards, it's impossible to test. .. Agile testers are exploring the software and performing bug finding and validation on the fly."[11] In contrast, in the ‘90s there was a wave of quality standards such as CMMI, ISO 9000 family, and TQM which current role will be reviewed.

Apart from the fact that these concepts don't really fit to be agile, the question is whether mixed concepts are the solution for future projects at all. And that's where, in addition to the practical reasons mentioned above, this work will also emphasize the theoretical background and status quo in research about software quality management (SQM). In times when it is not about machines being connected to the Internet anymore, but machines autonomously interact with each other and with us humans, there is a correspondingly high relevance to investigate current studies about SQM in relation to such modern software intensive projects. To translate this into an objectified example, this research will also set a focus on autonomous driving. "[Autonomous Vehicles] ... represent the perfect connection between digital and real world, an issue that stands in the center of Industry 4.0."[12]

[9] Lasi et al. (2014), p.239
[10] see Hoda et al. (2018), p.62
[11] Hutcheson, M. L. (2003), p.15
[12] Pieroni et al. (2018), p.10

1.2 Objective and research questions

As indicated in the introduction, there are several objectives to work through in this research paper. An in-depth overview of SQM related to Industry 4.0 and Autonomous Driving will not only fill a research gap, but also reveals whether or not a new wave of quality standards is coming. Maybe in the near future a change of mind will take place of how quality is understood due to new requirements. Thus, the present work answers the following research questions:

- *„Which new SQM methods, standards or concepts have been developed in recent years?”*
- *„Do these findings meet the new requirements for modern software intensive projects in Industry 4.0 and Autonomous Driving?“*
- *„How does the understanding of SQM change?*

The three core terms SQM, Industry 4.0 and Autonomous Driving all have large margins for interpretation. “The term Industry 4.0 collectively refers to a wide range of current concepts, whose clear classification concerning a discipline as well as their precise distinction is not possible in individual cases.”[13] The same can be said about the other two terms. Therefore, the terms will be framed and defined in order to be able to analyze them in a fixed framework. This research offers a concretely measurable current state. Methods and concepts in software quality management will be identified, which may be transferred to other examples, industries, and fields. The methodological consideration will not only supplement existing and future scientific studies, but will also show the further development of existing concepts, completely new concepts or the absence of any SQM concepts.

The results will enable both a historical and a new classification of software quality management procedures and approaches and a better understanding of what quality means in this context. It is important to make clear that the considerations in this paper will not be excessively technical and will not give full depth explanations of some mentioned development concepts like SCRUM or quality standards like ISO/IEC 25010[14]. Instead, the determining ideologies and the structures will be explained in

[13] Lasi et al. (2014), p.240
[14] Estdale J., Georgiadou E. (2018), p.494

order to provide a meaningful reference for the overall picture. The theoretical considerations are covered by an examination of the state of research and are supplemented by selected examples from practice. Special focus is placed on the reference of SQ in the field of Industry 4.0 and especially Autonomous Driving. Existing and future requirements of these domains will be identified, and it will be checked whether new SQM methods, standards or concepts exist to meet these requirements. The results will answer the stated research questions and therefore bring together domains in which not much research has been done yet. At the same time economic and social concerns of the present and future in practice will be shown.

1.3 Structure and research method

Figure 1 presents the structure of this work and breaks it down into its relevant task.

Figure 1 - Structure of this work

This representation should help to quickly grasp the set-up of this work. The main part takes place in the three grey highlighted chapters. The other parts play an introductory, preparatory, or supportive role. To put it quite simply: New methods, standards and concepts are looked at (chapter 2.2), then the requirements in the two fields of investigation are worked out. Afterwards an analysis is made of how the new methods fit these requirements (chapter 3) and the results are summarized in chapter 4.

Now that the basic concept has been clarified, the structure will be explained in detail and, in doing so, the research method will be introduced.
Following the introduction in this first chapter, the second chapter defines the analytical framework and is furthermore quite important to have a common understanding for further reference. Once you start thinking about SQM, things can become quite confusing, because one cannot avoid considering the much larger field of general quality management (QM). The same applies to the closely related software development life cycle (SDLC) and some other related topics like quality assurance (QA). Chapter 2.1 is therefore about uncovering the clutter and provides clarification with a lot of these terms. Subchapter 2.2 contains a structured literature analysis that is conducted through books, journals, tech blogs, web articles, annual reports, and trend analyses from renowned consulting firms or specialist committees. In the two-part chapter, the status quo in academic research and best practices in SQM are examined. This forms the basis on which the two fields to be examined will be checked on. Next in subchapter 2.3, these two fields, Industry 4.0 and Autonomous Driving, will be determined and brought in relation to SQM. Chapter 2.4 describes the subsequent analysis process to which the entire third chapter is devoted.

This analysis provides an assessment of whether current approaches meet the SQM requirements of Industry 4.0 and Autonomous Driving. Examples and explanations are used to illustrate whether current methods are used or implemented.
The results of these findings are presented in chapter four and answer the second research question with a well-structured table followed by answering the third question about a possible new understanding of SQM. To complement this, the fifth chapter touches on controversies and discussion points as additions and offers a critical appraisal. The last chapter summarizes everything and gives an outlook and starting points for further research.

As mentioned above, the literature analysis shall follow a clearly defined procedure to ensure stringency. Hence inclusion and exclusion criteria are defined, bearing in mind that both the state of science and practice are considered to change fast. In addition, the scientific literature research with its higher precision differs somewhat from the research on practical examples with a more semi-structured qualitative-quantitative approach due to the nature of the sources. To a certain extent, this leads to an only relatively reproducible but in any case, fully comprehensible system.

As a first step for the scientific literature research, a suitable list of databases was compiled. The selection was based on recommended databases in the field of economics and computer science from the University of Stuttgart and complemented with the results of a somewhat older but all the more fitting study by Brereton et al.[15] In addition, contributions from selected journals of a rating of the German Association of University Teachers for Business Administration (Verband der Hochschullehrer für Betriebswirtschaft e.V.) and SCImago were considered.

It would go beyond the scope of this work to further explain the research method in every detail, so the extensive work was summarized in the self-explanatory table 1. Lots of work was put into a particularly comprehensive research. All databases, search engines, as well as other sources were listed and tested with the most relevant search terms listed on the left side of the table. Some sources got directly excluded, mainly because of quantitatively low results or because other sources have shown the same results already. The left side of the table clearly shows which general restrictions have been made, which bibliometric aspects have been considered and explains in detail which criteria and additional keywords have been considered. Although some of the neighboring terms may tempt to delve deeper into them, the focus remained on the selected terms, and the additional keywords were only used in a second step, in combinations or only occasionally for searching.

The table also contains the more informal sources for search for practical examples, for which possible new SQM concepts will be analyzed. The free web search was restricted mainly with regard to the publication form and the fit to the definitions of Industry 4.0 and Autonomous Driving in this paper. As already mentioned, there remains a little noise and only relative reproducibility, but this research method offers us a sufficiently clear framework and at the same time enough leeway to give tangible examples in the three very complex subject areas for this study.

[15] see Brereton et al. (2007), p.577

Step 1 - The general set-up	
• Suitable and recommended databases have been selected	
• Started broadly to cover all three topics SQM, Industry 4.0 and Autonomous Driving ample	
• Added certain journals in particular, based on high rankings	
→ VHB-Jourqual and Scimago Jounral Ranking in Information Systems	
http://vhbonline.org	https://www.scimagojr.com
• Included statistical tools like Statista, Google Trends, Google Ngram	
• Included sources for practical examples e.g. YouTube, Tech-Blogs, Reports	
Step 2 - Limitations & considerations	
• Focus on very recent sources (2018 and 2019)	
→ very frequently cross-referenced sources were occasionally included even if older	
→ sources older than 2016 occasionally included only if deemed highly important	
• Languages: mainly English sources, partly German sources	
• Bibliometrics (e.g. Citation Count) taken into account, but not overrated, due to novelty of topic	
• Standards, were mainly obtained directly from the ISO and DIN websites, not from databases	
Step 3 - Keywords	
English	**German**
"Software quality management"	"Software Qualitätsmanagement"
"Software Quality"	"Software Qualität"
"Industry 4.0"	"Industrie 4.0"
"Autonomous Driving"	"Autonomes Fahren"
"Software Development"	**Keyword search methods:**
"Software-Intensive Systems"	• Various combinations were used
"Software development life cycle"	→ AND / OR combinations, for example:
Additional keywords:	→ "Software Quality" AND "Industry 4.0"
Improvement, Assurance, Control	→ (Software OR Quality) AND "Industry 4.0"
Planning, Model, Method, Concept	• With and without quotation marks
Characteristics, Requirements	→ various sequences were used
Testing, User Acceptance, Case study	• Suggested keywords by databases
Guidelines, Agile, SQM, SQA, SQC etc.	→ many databases offered special functions
Step 4 - Abstract examination	
Abstracts of articles, book introductions and excerpts from blogs and reports were examined. In the literature in particular, it was examined whether the contributions refer to software quality and its management, whether the studies present existing or new methods, or whether they refer to concepts of SQM as a whole. For the topics Industry 4.0 and Autonomous Driving it was examined whether a current state of affairs was presented and whether requirements could be derived from the contributions.	
Step 5 - Concluding remarks	
• Some sources were used that were only found by cross-references in other findings	
• Explorative research character, due to three vast thematic fields (SQM, Ind. 4.0 and AD)	
→ literature focused for the status quo of SQM → practical focused in the fields investigated	
• Especially with Industry 4.0 and AD it has been taken care that the sources are very current	

No.		Database Name	Link (Institutional Login via University of Stuttgart)	In- / Excluded	Rationale / Explaination
1	recommended by University of Stuttgart	University of Stuttgart Library Catalog	https://stg.ibs-bw.de	Included	interesting contributions, remarkably up-to-date
2		Library of the Institute of Business Administration	http://swb.bsz-bw.de | Library Code: [93]	Excluded	search in this specific department produced rarely better results than ↑
3		Elektronische Zeitschriftenbibliothek (EZB)	https://rzblx1.uni-regensburg.de	Excluded	few results through free text search, journals already covered by other databases
4		OPUS - Publication Server of the University of Stuttgart	https://elib.uni-stuttgart.de	Excluded	Interesting contributions, but few were considered relevant in this case
5		Emerald Insight	http://www.emeraldinsight.com	Excluded	few and rarely relevant results (only when looking for older contributions)
6		**Springer E-Books via SpringerLink**	https://link.springer.com	Included	great search results, covered a lot of the results from other databases
7		OECD iLibrary	https://www.oecd-ilibrary.org	Excluded	few and rarely relevant results
8		WISO	https://www.wiso-net.de/dosearch	Excluded	few and rarely relevant results
9		De Gruyter Online - E-Books	https://www.degruyter.com	Excluded	few and rarely relevant results, Google Scholar found same results
10		Hanser eLibrary	https://www.hanser-elibrary.com	Excluded	few and rarely relevant results, Google Scholar found same results
11		ProQuest Ebook Central	https://ebookcentral.proquest.com/lib/uni-stuttgart	Excluded	good results, however relevant contributions already covered by Google Scholar
12		E-Books Nationallizenzen	http://gso.gbv.de/	Excluded	few and rarely relevant results
13		Wiley Online Books	http://onlinelibrary.wiley.com/	Included	great results, when the right combination of keywords was found
14		SPIE Digital Library	https://www.spiedigitallibrary.org	Excluded	few and rarely relevant results
15		Web of Science (by Clarivatis Analytics)	https://www.webofknowledge.com	Included	great results, when the right combination of keywords was found
16		Business Source Premier (via EBSCOHost)	https://search.ebscohost.com/Login.aspx → Institutional Login via University of Stuttgart	Excluded	There have been good results, but it quickly became clear that these won't be used due to better findings in other databases.
17		EconLit (via EBSCOHost)		Excluded	
18		EBSCOHost eBook Collection		Excluded	
19		EconBiz	https://www.econbiz.de	Excluded	rarely relevant results, that weren't covered though other databases
20		JSTOR	https://www.jstor.org	Excluded	rarely relevant results, that weren't covered though other databases
21	REC by Brereton et al.	ACM Digital Library	https://dl.acm.org	Included	good search results, highly ranked journals included
22		**IEEE Xplore**	https://ieeexplore.ieee.org	Included	good search results, highly ranked journals included
23		**Google Scholar**	https://scholar.google.com	Included	great results | has found many of the same results as other databases
24		CiteSeer Library	https://citeseerx.ist.psu.edu	Excluded	keywords did not provide satisfactory results
25		**ScienceDirect (by Elsevier)**	https://www.sciencedirect.com	Included	pretty good results on Elsevier, mainly ScienceDirect was had good contributions
26		Inspec (via Elsevier)	https://www.engineeringvillage.com	Included	
27		EI Compendex (via Elsevier)		Included	
28	extra added journals	MIS Quarterly	https://www.misq.org	Included	All three journals were represented in one of the databases listed above, and had interesting contributions. However, especially a current state on SQM would be a valuable addition.
29		Information Systems Research	http://pubsonline.informs.org/journal/isre	Included	
30		Information Systems Journal	https://onlinelibrary.wiley.com/journal/13652575	Included	
31	added statistical tools	Statista international	https://www.statista.com	Excluded	In the course of this work, a number of suitable statistics were looked for in order to present or back up certain statements. In the end, however, no really relevant statistics were found that fit. Thus more suitable trend representations were found and implemented from surveys of consulting companies and committees. ↓
32		Google Trends	https://trends.google.com/trends		
33		Google Ngram	https://books.google.com/ngrams		
34	free web search	YouTube (e.g. MKBHD, Lew Later, Teslanomics ...)	https://www.youtube.com	Included	The free Google search was mainly used with regard to the four types of sources listed above it (Blogs, Reports...). In combination with the keywords listed on the left and a limitation to the last year, particularly current, practice-relevant content could be found.
35		**Blogs (TechCrunch, The Verge...)**	-	Included	
36		**Reports (Forbes Magazine, Business Insider, Reuters...)**	-	Included	
37		**Consultant Company's sites (McKinsey, BCG, KPMG...)**	-	Included	
38		Google	https://www.google.com	Included	
		The bold marked sources were used by far the most.	Of course 'included' doesn't automatically mean that contributions from these sources have been used.		*Important note: Not directly apparent in this table, is the fact that sometimes several rounds with different keywords were conducted. Among others, IEEE Xplore and Google Scholar contained exactly the same results that were considered relevant as other sources, which produced fewer results overall. Therefore, these sources with fewer results were then excluded.*

Table 1 - Research method

2. Analysis Framework

2.1 The definition of SQM

The term SQM consists of the three terms software, quality and management. Multiple perspectives allow to address each term on its own or a combination of two terms. All three terms are difficult to define considering the high speed of innovation, but the term quality is the most relative and perhaps most subjective of them. To better illustrate this, it helps to look at Garvin's five approaches to define quality, to which most current studies still refer:

1. Transcendent approach: quality is universally recognizable, cannot be defined precisely.
2. Product-based approach: quality can be measured precisely, it is related to quantitative attributes such as costs, durability and so on.
3. User-based approach: quality lies in the eyes of the beholder and is related to user's varying interpretations and their maximizing satisfaction of use.
4. Manufacturing based approach: quality in the eyes of the supplier primarily concerned with engineering and manufacturing practice. Requirements have a high priority and any deviation from them implies a reduction in quality.
5. Value-based approach: quality is defined in terms of price and costs. An affordable peak performance is desired, but has no well-defined limits and is difficult to apply in practice.[16]

It is essential to understand that the term quality brings its difficulties with it, but one should not get lost in the discussion about quality in general, but be concentrated on software. Therefore, it makes sense to cluster the terms software and quality (SQ) and ask how it can be operationalized to cover the management part. A qualified and up-to-date definition of SQ is referenced by D. Galin from the newest Standard IEEE 730-2014 the Institute of Electrical and Electronics Engineers (IEEE), which is "… among the most prominent developers of SQA [Software Quality Assurance] and software engineering standards, and have gained international reputation and standing in this area":[17] "Software quality is the degree to which a software product meets established requirements; however, quality depends upon the degree to which established requirements accurately represent stakeholder needs, wants, and expectations."[18]

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[16] see Garvin A. D. (1984), p.26
[17] Galin D. (2018), ch.1.1, para.1
[18] IEEE (2014), p.7

In the latest international standard ISO/IEC 25010:2011 Software engineering - Software product Quality Requirements and Evaluation (SQuaRE), a distinction is made between two quality models: (1) quality in use model and (2) product quality model:

Quality in use:	Product quality:
Quality in use defines five characteristics to outcomes of interaction with a system: 1. Effectiveness 2. Efficiency 3. Satisfaction 4. Freedom from risk 5. Context coverage	Product quality relates eight characteristics of a software product, or to a computer system with software: 1. Functional Suitability 2. Performance Efficiency 3. Compatibility 4. Usability 5. Reliability 6. Security 7. Maintainability 8. Portability[19]

Table 2 - Definition of software quality, according to ISO/IEC 25010:2011

In line with this, the ISO/IEC/IEEE 24765:2017 Systems and software engineering - Vocabulary standard always refers to documentation as an important component of software.[20] This can be translated in that the quality of software is also determined by the quality of the communication of competence or documentation. In other words, the quality of a software is only as good as the user who uses it. Secondly, it is only as good as it meets the requirements a user expects. And that is also important for the later course, when we look if new SQM approaches for software intensive projects in Industry 4.0 and Autonomous Driving are available.

In order to keep the focus on software, the general quality management (QM) will not be considered, and an overview of SQM will be given by Ivan Mistrik et al.: “SQM comprises three basic subcategories [Figure 2]: software quality planning (SQP) software quality assurance (SQA) and software quality control (SQC). Very often, like in the Software Engineering Body of Knowledge (Guide to the Software Engineering Body of Knowledge 2015), software process improvement (SPI) is also described as a separate sub-category of SQM, although it could be included in any of the first three categories.”[21]

[19] ISO/IEC Std. 25010:2011 (2011a), pp.3-4
[20] see ISO/IEC/IEEE Std. 24765:2017 (2017), p.414
[21] Mistrik I. et al. (2016), ch.1.2, para.1

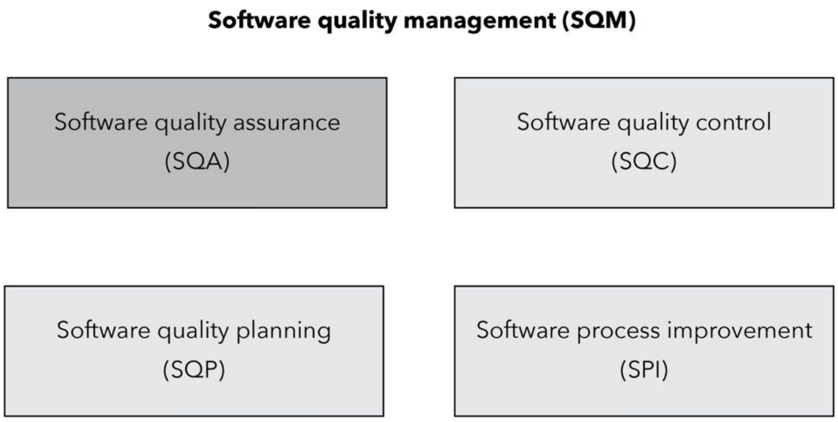

Figure 2 - SQM Overview, according to Mistrik I. et al. (2016), ch.1.2

Software has special characteristics that distinguishes it from any other type of product. "First and foremost, software is immaterial, such that all of the practical values for material products do not apply or are only transferable in a limited sense. Thus, software is not manufactured but ‘only’ developed."[22] That leads to a broader perspective where software could be seen as a tool that is constantly being further developed tool as opposed to an engineered finalized product. SQM can be considered as a sequence of activities that take place as part of the development process. SQM and software development are directly linked, and the results of SQM activities can be used as input for development activities. It is important to understand that there is this link between SQM and the software development life cycle (SDLC). Mehmet Söylemez and Ayca Tarhan aptly say: "It is claimed by software quality management that the quality of a software product is highly influenced by the quality of the software process followed to develop it."[23] Managing software quality therefore means that the four subcategories, as shown in Figure 2, are in some way intertwined within the software development process. And this is precisely where the connection between the concepts of software quality and the concepts of agile methods in relation to SDLC can be established. It is no coincidence that modern development methods follow agile approaches, since even quality related terms are often used in a confused - one could say agile - way. The terms SQA, SQC, SQP and SPI are all aligned pretty closely but they all mean slightly different things. There are many different arrangements, definitions and classifications of terms depending on where you look. Yet the terms are best understood as follows: “SPI addresses many aspects ranging from individual developer skills to entire organizations. It comprises, for instance, the optimization of

[22] Schieferdecker, I., Ritter, T. (2019), p.357
[23] Söylemez, M., Tarhan A. (2018), p.779

specific activities in the software life cycle as well as the creation of organizational awareness and project culture."[24] As mentioned above, the term can be seen as part of one of the other SQM activities, but sometimes, although rarely, SQM is seen as part of an SPI program.

In the software industry, different companies and industries interpret quality assurance and quality control quite differently.[25] The latest ISO/IEC/IEEE 24765:2017 Standard for software vocabulary gives the following definitions:

Quality Assurance:

"1. part of quality management focused on providing confidence that quality requirements will be fulfilled.

2. all the planned and systematic activities implemented within the quality system, and demonstrated as needed, to provide adequate confidence that an entity will fulfill requirements for quality."

Quality Control:

"1. set of activities designed to evaluate the quality of developed or manufactured products.

2. monitoring service performance or product quality, recording results, and recommending necessary changes." [26]

A note has been added to the definition of quality control that there is currently no uniform meaning in software engineering.[27] Daniel Galin states "Software quality control relates to the activities needed to evaluate the quality of a final software product, with the main objective of withholding any product that does not qualify. In contrast, the main objective of software quality assurance is to minimize the cost of ensuring the quality of a software product with a variety of infra structure activities and additional activities performed throughout the software development and maintenance processes/stages. … In summary,

1. SQC and SQA activities serve different objectives.
2. SQC activities are only a part of the total range of SQA activities."[28]

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[24] Jacobsen, J.W. et al. (2016), p.327
[25] see Sommerville, I. (2018), p.781
[26] ISO/IEC/IEEE Std. 24765:2017 (2017), pp.358-359
[27] see ISO/IEC/IEEE Std. 24765:2017 (2017), p.359
[28] Galin D. (2018), ch.1.6, para.2

Ivan Mistrik et al. define SQP as a preceding process: ".. SQP is defined at the project level that is aligned with the SQA. It specifies the project commitment to follow the applicable and selected set of standards, regulations, procedures, and tools during the development life cycle. In addition, the SQP defines the quality goals to be achieved, expected risks and risk management, and the estimation of the effort and schedule of software quality activities."[29]

These explanations give a good general understanding of the terms even if there are many interpretations, re-interpretations or misinterpretations out there. As stated, software quality (SQ) and achieving such, is directly correlated to its development process (SDLC). Therefore, the understanding and hierarchic arrangement of the terms can vary depending on the SDLC methodology or framework. The delineation of the terms in Figure 3 is very useful for orientation and clarification, although not applicable in all cases.

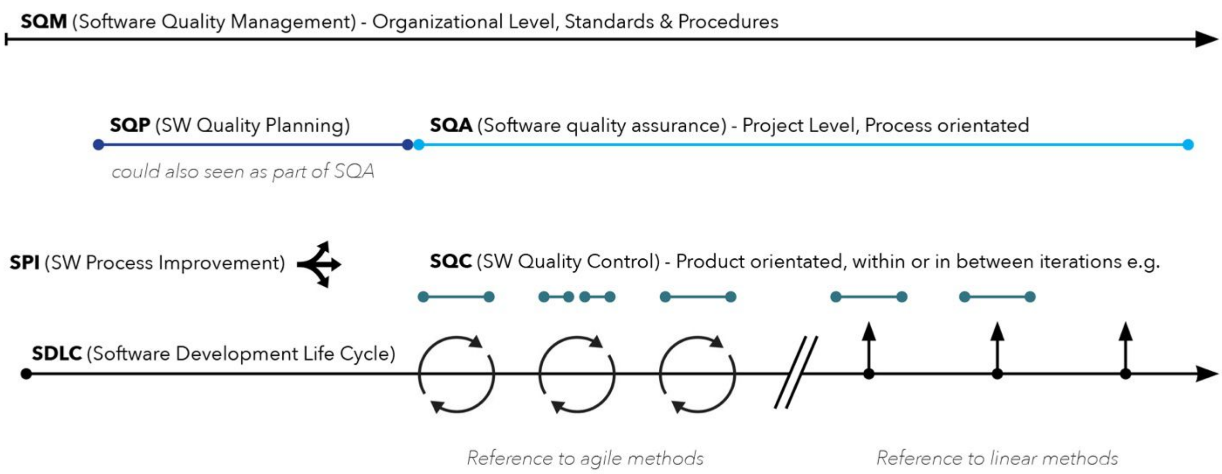

Figure 3 - SQM, SQA, SQP, SPI, SQC, SDLC Hierarchy

If a certain sequence of procedures in the development process takes place it is easier to match a hierarchical structural understanding. With today's agile software development philosophies, it is sometimes more difficult to distinguish between SQM activities, and therefore there are a lot of ambiguities with the discussed terms. [30]

[29] Mistrik I. et al. (2016), ch.1.2, para.1
[30] see Poston, R., and Calvert, A. (2015), p.749

The 13th annual State-of-agile report, which has become the largest, longest-running, and oft-cited agile survey, reports 97% of respondents' organizations practice agile development methods within their organization in 2019.[31] Software development processes have evolved in line with rapidly changing market requirements, and agile software development is the preferred choice for methods that promote speed and flexibility.[32] In the State-of-agile report, 74% (the highest percentage) of all respondents mentioned *accelerated software deployment* as a reason to adopt Agile. However, it is very interesting to note that the fifth most frequent reason (43%) was *improvement of software quality*.[33] It's precisely this relationship of agile methods and quality that is interesting. The question remains whether this can also be translated into complete SQM methods and their potential to meet the requirements of Industry 4.0 and Autonomous Driving.

The understanding of SQM and its connection with the creation process and thus agile methods that has now been created, allows a transition to the next chapter. As already mentioned, the term *management* in SQM already implies an operationalization and therefore a standardization for SQ. Process standardization can sometimes stifle creativity due to the role of design and creativity in the software development process, leading to worse rather than better software. Nonetheless, software standards play a very important role in software quality management.[34] ISO and IEEE are the two most important organizations for standardization to which this work frequently refers. Other noteworthy institutions are the American National Standards Institute (ANSI), the International Electrotechnical Commission (IEC) and the Electronic Industries Alliance (EIA).[35] There are numerous SQM related ISO standards. They address many different things like documentation, life cycle management, assessment, measurement, and testing.[36] With regard to SQM and Agile development methods, there are also other countless acronyms that emerge. The role of SQM is ultimately to identify and understand them and to unlock the relationship between standards, quality models, process models, frameworks and methods and any other resulting acronyms. Based on the results achieved today, SQ managers must have a vision for the broad directions to generate tomorrow's results.

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31 see CollabNet VersionOne (2019), p.7, URL see references
32 see Rodríguez, P. et al. (2019), p.135
33 see CollabNet VersionOne (2019), p.7, URL see references
34 see Sommerville, I. (2018), p.786
35 see Galin, D. (2018), Appx. A.1.2
36 see ANSI (2019), URL see references

2.2 State of the art in SQM

2.2.1 State of research in SQM

A suitable introduction to the state of the art in research in the field of SQM is offered by a study by Whee Yen Wong et al., who provide a roadmap (see Appendix) that will help selecting the best quality improvement method. The roadmap provides multidimensional criteria in a single high-level holistic overview and is intended for SMEs/SMIs of IT and non-IT businesses.[37] Their work and the resulting roadmap does not offer any new methods in itself, but rather states that the mere selection of the right method can be a decisive factor. It lists the four (IT related) QA and QC methods ITIL (Information Technology Infrastructure Library), ISO (previously mentioned), CMM/CMM-I (Capability Maturity Model Integration) and Six Sigma and underlines their ongoing relevance at the current point in time. In this context TQM is categorized as NON-IT-Related. However, Amal Alhassan et al. have published a relatively new study on the implementation of TQM to improve the software development processes, so there are approaches.[38] “ITIL is a widely-adopted body of knowledge and best practices for successful IT service management that links with training and certification.”[39] AXELOS, the company responsible for ITIS, also manages the noteworthy frameworks COBIT and PRINCE 2 / PRINCE 2 Agile among others.[40] "... The CMMI V2.0 model is a proven set of global best practices that enables organizations to build and benchmark the key capabilities that address the most common business challenges."[41] Six Sigma is a framework which can be roughly paraphrased like this too. It's not the intention at this point to explain all these methods, but mention that research on them still appears in many forms, more than ever. Various methods get blended and studies are made on how some of these frameworks can be combined with certain development methods (e.g. Agile, DevOp etc.) and how they can be adapted in specific industries. This conglomerate brings as many solutions as problems and things become more and more unclear. It’s not advisable to confuse management processes, frameworks, development methods and standards. But for sure it’s the combination of all of those that allows to create new principles for a great software quality management system.[42]

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37 see Wong, W.Y. et al. (2018), p.158
38 see Alhassan, A.M., et al. (2017), pp.38-44
39 Axelos (2019a), URL see references
40 Axelos (2019b), URL see references
41 CMMI Institute (2019), URL see references
42 see Aleksandrova, S.V. (2018) p.18

Currently, these are the tools managers have available to set up, update, and assign software quality policies to executives and address software quality issues.[43] A prime example is a study on the combination of CMMI specific practices with Scrum model.[44] H. Dahar and O. Roudies investigated the co-deployment of ISO 9001, CMMI and ITIL and concluded that their concurrent use is an asset for companies.[45] "In general, it seems important ... [that companies] start thinking about adapting several standards."[46] The ISO/IEC 25010:2011 (SQuaRE) standard was last reviewed and confirmed in 2017 but its current presence in the literature is tremendous.[47] It’s fair to say it presents the leading quality model for software *software-intensive computer systems*.[48] In addition the ISO/IEC/IEEE 90003:2018 is worth noting as an example for giving 'only' guidelines for the application of the rather generic ISO 9001:2015 standard to computer software in particular. ISO 9001:2015 is part of the ISO 9000 family which has far-reaching history. "ISO 9001:2015 sets out the criteria for a quality management system and is the only standard in the family that can be certified to."[49] It's remarkable that based on these fairly old roots the current state of affairs still shows a high relevance of these standards in relation to software quality management.

“Many [companies] ... adopted ISO for the reasons of 'value of the standard', 'sales and marketing advantage' and 'company requirements'."[50] Yangyang Zhang et al. propose that “… the next round of revision, ISO/IEC 25000 [consequently ISO/IEC 25010] will give more focus on the technology related to the quality in use and even defines it into an independent standard to improve user experience in quality measurement.”[51] Thus state of the art in literature doesn't directly reveal a new universal method but rather indicates a clear trend towards end-user orientated quality awareness, and corresponding approaches. This user experience orientation is in line with the direction of visualization and simulation methods with user acceptance tests, which will be mentioned later. It must be noted that this orientation has partly been lost in the field of quality assessment. Even in the last decade with agile development methods, which should involve the user more, it was not explicitly included in SQM

[43] see Galin, D. (2018), ch.4.2, para.1
[44] see Amer, S.K. (2019), p.898
[45] see Dahar, H., Roudies, O. (2018), pp.451-459
[46] Ibid. p.459
[47] ISO/IEC Std. 25010:2011 (2011b), URL see references
[48] see Estdale, J., Georgiadou, E. (2018), p.492
[49] see ISO (2019a), URL see references
[50] see Wong, W.Y. et al. (2018), p.155
[51] Zhang, Y., et al. (2018), p.384

methodologies as it will be the case in the future.[52] Examples include a quality assurance process that makes use of emojis to reveal emotions within analyses for decision making[53,], a classification model of software quality according to users' perception[54] and a proposal of an evaluation method extracting users' feedback from records stored in help desk databases.[55] "... Quality in use can show how people feel very well when they are using the software products."[56]

Muhammad Azeem Akbar et al. take up several of these observations in their proposal to form a new software development method. Their model for improving the software development process and thus ensuring software quality is called the AZ Model and will be explained in more detail in the next subchapter. With their model they claim to fill the gap between existing methodologies and eliminate their limitations.[57] Accordingly, the authors list some (older, not necessarily outdated) development methods which have not been mentioned. They consider the Waterfall Method, the iterative methods RUP (rational unified process model) and Spiral Model as well as the V-Model as heavyweight methodologies. In contrast, agile methods are considered lightweight methods. In this field they refer to Extreme programming (XP), as well as Scrum, Dynamic systems development method (DSDM), Crystal Clear (by Alistair Cockburn), Feature-driven development (FDD), and the already mentioned PRINCE 2. The authors don't fail to mention that the last-named methods aren't development methods, but rather process models.[58] This separation between heavyweight- and lightweight-methods is quite common in current literature. These explanations underline that there are still large gaps in the right mix of methods and in the end-user focus.

Marco Kuhrmann et al. present an analogous perspective with their ongoing research on Hybrid Software Development Approaches. In their most recent paper, of which the results for practice will also be discussed in the subsequent chapter, they have conducted an exploratory multistage survey and collected data from 69 practitioners across Europe. Their underlying research and results for future research (apparently planned) underline that especially the pairwise combination of methods is clearly a strategy for many companies of all types and industries.[59]

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[52] see Arslan, H. (2018), p.83
[53] see Scherr, S.A., et al. (2018), p.45
[54] see Mendonca, J. et al. (2018), p.298
[55] see Fernandes Lima, A.C. (2018), p.47
[56] Zhang, Y., et al. (2018), p.384
[57] see Akbar, M.A. (2018), p.4819
[58] see Ibid. p.4812
[59] see Kuhrmann, M. et al. (2019), p.26

A cutting-edge perspective is offered by Robin Poston and Ashley Calvert, who conducted interviews with a panel of top visionaries in artificial intelligent systems, software testing, user experience, and automated systems about the future of SQM best practices, approaches, user acceptance and user involvement throughout the development life cycle.

Their findings state that "future process will infuse end user perspectives in the design and validation of new software at the front end of the development life cycle."[60] They reaffirm the indispensable role of agile, or rather Scaled Agile Frameworks (SAFe) and that so-called user acceptance testing (UAT) teams should be built into scaled agile frameworks and application life cycle management systems. These teams shall develop risk profiles and *technical debt* ratios and make test environment availability, continuous integration, automated testing and other forms of testing a rated criterion, so UAT could be transferred to an operational readiness evaluation.[61]

The next method mentioned is much more tangible and refers to visualization tools. Since the cost-quality correlation of such tools has reached a meaningful level, users and creators of software can talk descriptively about the final product before a single line of code is even written. Created simulations of software designs can mimic the real end product and enable innovative communication for revenue-enhancing ideas through implementing users' needs and avoid refinishing that would otherwise have to be done.[62] The authors also mention methods in the field of Augmented Reality, Cognitive Computing and Artificial Intelligence, and explain how the combination of all these approaches could possibly result in a fully automated user testing systems. "The focus is to design requirements visually within simulation to allow real end users to 'test drive' the software before it is created. Using operational scenarios in the simulations based on known usage patterns, autonomous artificial intelligence systems can use neural networks to scan actual live production systems for real user activities."[63] The work of Poston and Calvert is one of the few studies that is directly oriented towards new SQM methods and even for 2019 presents seemingly futuristic prospects, some of which will be discussed in the next practice-orientated related chapter.

[60] Poston, R., Calvert, A. (2015), p.752
[61] see Ibid., p.753
[62] see Ibid., p.754
[63] Ibid., pp.755

2.2.2 State of best practices in SQM

In order to present the current state of practice in relation to SQM, the methods and trends mentioned in the previous chapter offer a great point of entry.
The roadmap (see Appendix) presented by Whee Yen Lan et al. mentions very well-known companies that successfully use the listed methods in a column labeled *success stories*. Among others, Disney, Microsoft, IBM, Hewlett Packard, Philips, Dell and Motorola are listed - all of which are also in the top 500 of the Forbes Global 2000 list - just to get a perspective of magnitude.[64]

It becomes a bit more difficult to drop numbers from practice regarding the mentioned ISO standards. “ISO does not perform certification.”[65] Independent third-party companies certify organizations to an ISO standard. An official ISO survey exists, but unfortunately no ISO 25000 (or 25010) statistics are included. A rough indication is the fact that over one million companies are ISO 9001 certified.[66] This barely says anything about software in particular, although the ISO 90003 standard previously mentioned comes in place "... as it provides a much needed interpretation of ISO 9001 in a language appropriate to software development."[67] In practice, it's difficult to find figures on software-related ISO standards. Notably, the third largest software company in the world, SAP, advertises on its own website that its solutions are derived from the ISO 25010 software quality model.[68] Although it's not technically related to software quality, it's very important to note that another family of ISO/IEC standards is making its debut in practice. Major enterprises like Google[69], Facebook[70], and Apple[71] promote their ISO/IEC 27000 family certifications, which helps companies to ensure the security of information assets.[72] As listed in chapter 2.1, security is a quality characteristic of software products, and in 2019 one could easily argue that information security in particular should not only be implied but also strongly focused. Another incentive to think outside the box and to expand the quality concept, is given by ISO’s involvement into the sharing economy.[73]

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[64] see Forbes (2019), URL see references
[65] Charlet, L. (2017), URL see references
[66] see ISO (2019a), URL see references
[67] Naden, C. (2018a), URL see references
[68] see SAP (2019), URL see references
[69] see Google (2019), URL see references
[70] see Nain, S. (2019), URL see references
[71] see Apple (2019), URL see references
[72] see ISO (2019b), URL see references
[73] see Naden, C. (2018b), URL see references

The sharing economy is one of the fastest-growing areas of the world economy and prime examples are - of course software companies - like Uber and AirBnB.[74] “In order for the Sharing Economy to reach the next stage of growth it will need to directly confront the issues of uneven quality.”[75] “Consumers may pay less and get new forms of goods, services or experiences, but questions are sometimes raised over privacy, reliability or trustworthiness.”[76] It's not that these concerns wouldn't be considered in the current definition of software quality. But since there's room for interpretation of the characteristics of quality of use and product quality, it's important that these aspects are not overlooked. The ISO offers guidelines and a framework for the Shared Economy in the form of the IWA27 (International Workshop Agreements).[77] Especially with regards to the field of software-intensive systems (Industry 4.0 and Autonomous Driving) discussed afterwards, it's crucial to give impulses for thought that software will expand into practically all areas of life and that the concept of software quality will thus become an integral part of the concept of quality in general and in all conceivable forms. Modern SQM in this sense also demands to think backward from existing industries to software, and not just forward thinking from software to new industries.

Muhammad Azeem Akbar et al. propose a new model to ensure software quality. As mentioned in the last chapter, they go over existing models, drew comparisons and then introduce their AZ-Model based on their learnings. “The state of the art indicates that the main contradiction between different methodologies should include adoptability and predictability, should be people-oriented and process-oriented, requirements collection and requirement change management.”[78] The authors claim to fill the gap and eliminate the limitations of methodologies. The AZ model consists of three phases: the customer participation phase, the development phase and the release phase.[79] The structural layout and sequence of the model can be seen in Figure 4. At first glance, the model may look very straightforward and simple, almost too hierarchical and old-fashioned. Consequently, a few things should be pointed out. For one thing, in the first phase the prototyping tool is to address customers, nonfunctional requirements, and usability requirements. Secondly, with regard to

[74] see Naden, C. (2018b), URL see references
[75] Wadhwa, T. (2018), URL see references
[76] Naden, C. (2018b), URL see references
[77] see Naden, C. (2018b), URL see references
[78] Akbar, M.A. (2018), p.4819
[79] see Akbar, M.A. (2018), p.4813

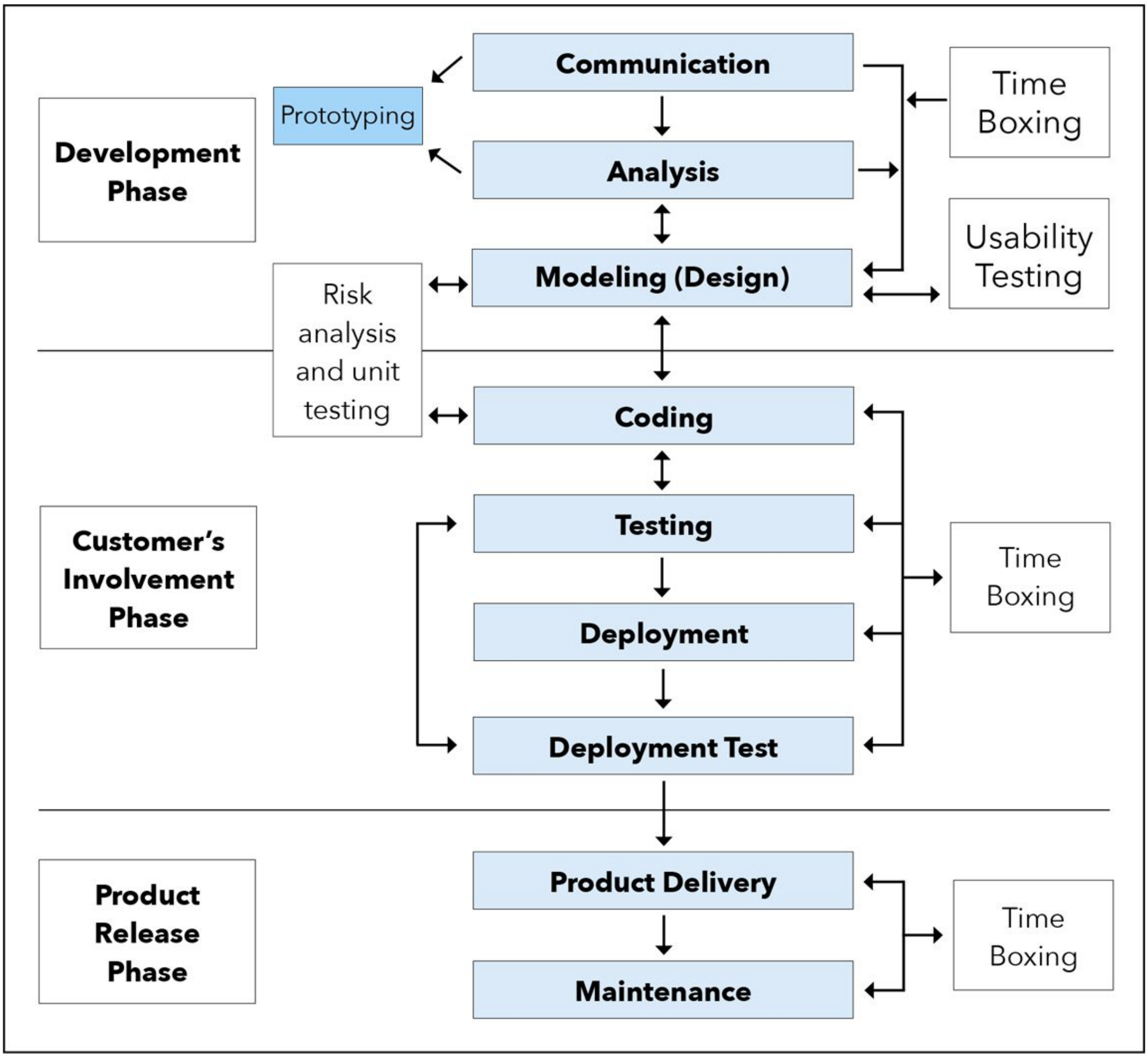

Figure 4 - AZ-Model, according to Akbar, M.A. et al. (2018), p.4813

quality, the authors write: "While comparing both methodologies, a customer is involved in heavyweight methodology only until requirement gathering, while customer is involved throughout the SDLC in lightweight methodology. Often both the fore-mentioned methodologies exhibit negative impacts. Therefore, according to the proposed model, a customer is involved until completion of a satisfactory design."[80] The fact that this model is a combination of several methods can certainly be seen. With regard to end-user orientation, however, it can be criticized that the involvement of the customer only takes place in the first phase and that time-boxing for design processes is generally problematic. Contrary to this, the authors argue that unit testing together with usability testing takes place before the development phase in order to analyze and minimize risks. In addition, “specialized project management" should

[80] see Akbar, M.A. (2018), p.4814

ensure that every task and every phase is well managed and that resources will be maximal utilized.[81] The authors have conducted a survey with 22 participants who have used the model in their companies. The statistical results indicate that the AZ model is highly effective for software companies to produce a quality product within a specified time and budget. Further studies, including comparisons with other methods, are planned.[82]
Assuming a specific premise, a certain regression to a less agile process method could actually be very interesting. If prototyping in the first phase would allow hyper-realistic simulations or visualizations as described by Poston and Calvert, then the AZ-Model would actually be a great, streamlined option.

The survey by Marco Kuhrmann et al. mentioned in the previous chapter ties in very well to this concept. Their survey not only underscored the orientation of the current research, but also provides multiple key takeaways about the current state of practice. The authors refer (more or less) to the same methods as Muhammad Azeem Akbar et al. and Hybrid Approaches of course means that traditional and agile approaches are combined. Traditional can be interpreted as heavyweight, agile as lightweight. Hybrid Approaches enable to benefit from both worlds by providing customers and management with a secure environment (heavyweight methods/standards) and developers with the flexibility (lightweight methods) they need.[83] This picks up the observation of the combination of methods. In addition, the survey revealed that most respondents to the survey stated that the hybrid development approaches were the result of experience. Often Scrum and the waterfall model were combined just like Scrum and Kanban.[84] "[The] .. analysis revealed that a few base methods served as an umbrella for integrating the different approaches."[85] Two much larger surveys clearly confirm this. The 2019 Scrum Master Trends Report shows that "81% are using Scrum with other agile practices, i.e. Kanban, DevOps, XP".[86] The 13th annual State-of-agile report mentions Scrum, Scrum/XP and other hybrid methods as the three most used agile methodologies. The same report states that most agile projects are

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[81] see Akbar, M.A. (2018), p.4822
[82] see Akbar, M.A. (2018), p.4821
[83] see Kuhrmann, M. et al. (2019), p.31
[84] see Ibid. p.26
[85] Ibid. p.26
[86] Wolpers, S. (2019), URL see references

successful, with *customer/user satisfaction* and *quality* in first and fourth place to measure this success.
The clear trend towards an even stronger end-user focus identified in the previous chapter is backed up in practice by results from World Quality Report 2018-19. “End-user satisfaction is the top QA priority”[87] A strong end-user orientation inevitably requires feedback from the user. Websites are a good example in this respect, especially because some of them represent browser-based software systems nowadays. In practice we can observe real users (actually watch them), conduct surveys (Qualaroo, SatisMeter) use analytic tools & heatmaps (Google Analytics, MixPanel, HotJar), do A/B Testing (Optimizely) or use Remote User Feedback (UsabilityHub) or User Playback Videos (FullStory, UX Cam).[88] This can be transferred to other domains with corresponding software for testing.

At this point it is important to recall the hierarchical understanding of SQM in chapter 2.1. Testing is definitely associated with software quality, but is also a separate issue. Depending on the process method or development method used, testing can take place at different points in the SDLC and therefore can be considered (a relatively small) part of SQM, or more specifically part of SQA or SQC.
For SQM it's important to understand that with all of these developments and current state of affairs it's not about Scrum, Agile and therefore Agile-Testing or testing in general. Agile practices have matured and everything that goes with it belongs to a trend of the last decade and is nowhere new. Without going into detail, it should be mentioned that Continuous Testing (CT) (together with Continuous Integration (CI) and Continuous Delivery (CD)) have proven to be key catalysts for enabling quality at speed and that continuous testing is by far the most challenging.[89] "Continuous Testing is the process in which the code integrations that are built during the Continuous Integration process get sent into a pipeline of various tests (integration, system, performance, regression, and user acceptance to name a few)."[90] And this is exactly the new step: As already quoted above by Poston and Calvert, especially UAT/End-User Testing will take place earlier in the SDLC and not (as usual) as one of the latter steps. In other words, verification (developing the system right/properly) is crucial, but

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87 Isaacs, M. (2019), URL see references
88 see Aggarwal, B. (2017), URL see references
89 see Dunlop, C. (2017), URL see references
90 Kaiser, A. (2019), URL see references

validation (developing the right system) moves further into the spotlight.[91] It's about that slight shift towards the use of (scrum-)hybrid methodologies and the seamless integration of end-user testing (known as the earlier mentioned UAT). “UAT events needs to be transformed away from just another phase of software testing to become about validating that the end users' needs and expectations have been met.”[92]

“The market for quality management software will receive a Rapid Boost in 2019 due to high emerging demands by forecast to 2023.”[93] Correspondingly, the concepts featured by Poston and Calvert are promising examples, a few of which will now be presented. Figure 5 lists an overview of the different target areas of tools for Human-computer interaction (HCI) driven development. Combined this illustrates their vision of the future of SQM best practices.[94]

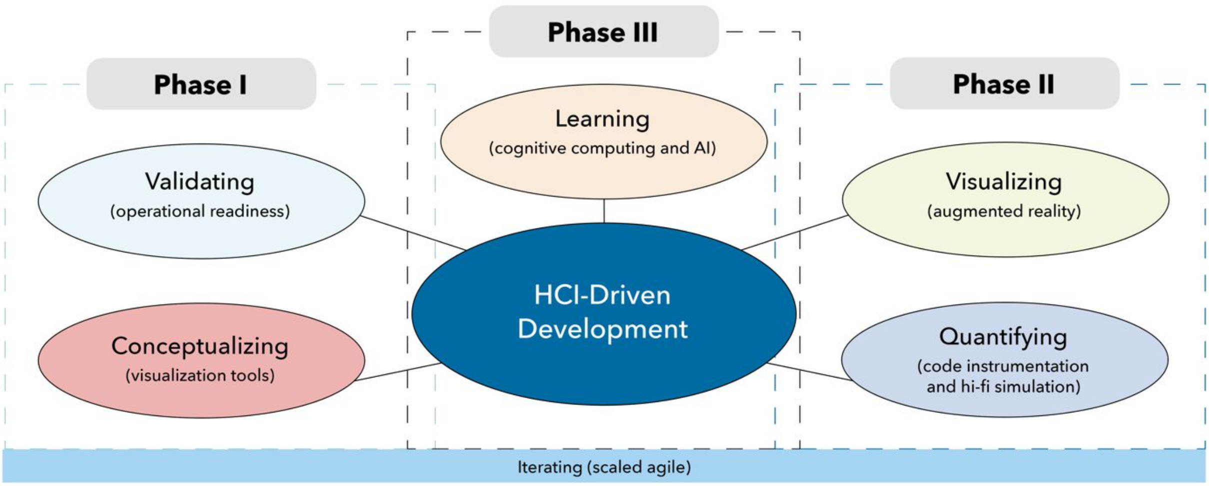

Figure 5 - HCI-driven Dev., according to Poston, R. & Calvert, A. (2015), p.752

Previously, validation and conceptualization were mentioned with respect to prototyping within the AZ-Model. The software iRise (www.irise.com) seems like a very adequate and representative example, since one can speak of a visualization tool here, but it is explicitly advertised as a responsive prototyping tool.[95] This fits with regard to the interpretation of visualization tools for prototyping in the AZ model. iRise is a platform that combines the rapid creation of wireframes, mock-ups and interactive prototypes with feedback features and inline requirements gathering. It supports going from sketchy whiteboard blueprints to wireframes and mockups. Photoshop or Sketch

91 see Easterbrook, S. (2010), URL see references
92 Poston, R., Calvert, A. (2015), p.750
93 Sawant, A. (2019), URL see references
94 Poston, R., Calvert, A. (2015), p. 752
95 see iRise (2019a), URL see references

(still the number one tools among UX designers) files can be imported, besides existing websites can be imported and translated to prototypes through screenshots.[96] The major advantage and the big difference is that the prototypes have actually implemented interactions (much of it runs automatically) resulting in logical and highly immersive experiences. Designed buttons, text fields/inputs, buttons, sliders etc. already have a real function and can even be provided with direct requirements. These visualizations are responsive (adapt to different screen formats) and can be tested directly on end-user devices. It's certainly fair to say that this can be seen as HCI-driven testing and maybe even HCI-driven development. It remains to be said that iRise works and collaborates with the most widely used ALM (Application Life cycle Management) tools (e.g. Jira, HP Quality Center, IBM Rational Software, Google Apps, Version One, ALM, Blueprint and others). In addition, it is important that although enterprise plans are individually priced, a single user account with $19 per month represents that this tool is definitely very affordable.[97]

Lightning Platform by Salesforce and InvisionApp (www.invisionapp.com, a German company from Düsseldorf) offer alternatives to iRise. However, they lack the immersive interactive part and hence are more on the level of Photoshop, Sketch or Adobe XD. It's eye-catching that even the German company has mainly US-American customers (namely AirBnB, Lyft, HBO, Netflix, Amazon)[98], just like iRise has large customers from all industries worldwide, but mainly customers from the USA.[99] If representative conclusions may be drawn remains open, but such observations are certainly of interest for SQM. Although the USA only ranks third among the most mature digital countries after Singapore and Sweden, it's definitely the biggest.[100] With reference to Industry 4.0 and Autonomous Driving, iRise's customers in the automotive industry (Ford, Fiat, Toyota, General Motors) and many in the manufacturing industry are worth mentioning.[101]

In terms of Augmented Reality, Cognitive Computing and Artificial Intelligence things might be not quite there yet. The tool user testing (www.usertesting.com) follows the approach to offer companies, who want to test their software, to get feedback on almost every product issue within a few hours. Depending on requirements or progress in the

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[96] see iRise (2019b), URL see references
[97] see iRise (2019c), URL see references
[98] see InVisionApp Inc. (2019), URL see references
[99] see iRise (2019d), URL see references
[100] see Andriole, S. (2019), URL see references
[101] see iRise (2019d), URL see references

development process, trained, instructed or totally blue-eyed testers can try out applications according to specifications (or even without any specifications) and provide feedback via video snippets or video interviews.
"Applause [www.applause.com] assembles custom teams of vetted professionals to test any device/OS combination in the world."[102] They provide skilled, certified testers in dedicated teams committed to develop a deep understanding of their clients' SDLCs. “Crowdtesting is becoming an integral best practice for many leading companies as it provides the scalability and coverage needed to test in today’s SDLC.”[103] On the contrary, one could claim that this approach is only sort of a recruitment agency.
These approaches are actually only a preliminary stage to what can actually be aspired to. From a customer perspective (e.g. SQ Manager, Software Development Company) it may be a step forward to get such real end-user feedback in such a convenient and fast way, as opposed to old school methods with expensive and lengthy meetings, workshops or other scenarios. Companies such as UserTesting or Applause could of course already store data and information about typical user behavior in order to later transform it into an artificial intelligence, which could then be used to mirror and simulate real users for continuous automated testing systems. "Future generations of automating testing activity will involve cognitive chips, e.g., the latest SyNAPSE chip by IBM."[104] This Cognitive Computing Chip is designed to mimic the human brain's perception, cognition and response capabilities.[105] In 2017, a small New York-based company had already attracted attention with the implantation of microchips under the skin of its employees. The chip was only RFID-enabled though and all it could do was open the office building or pay for food in the cafeteria.[106] In combination with chips, such as those from IBM, autonomous systems could be created. Thereby virtual end users based on artificial intelligence could interact with simulated versions of new software to utilize reality-driven operational scenarios to perform user acceptance validation before the code is written.[107] Again, it must be remembered that testing is only a small part of SQM. Nevertheless, there’s no need for new management and structure processes. Rather, it will be disruptive technology that will change SQM long term. And the beginning could be especially realistic in testing, even if it still seems futuristic.

[102] Applause App Quality Inc. (2019a), URL see references
[103] Applause App Quality Inc. (2019b), URL see references
[104] Poston, R., Calvert, A. (2015), p.754
[105] see IBM (2014), URL see references
[106] see Astor, M. (2018), URL see references
[107] Poston, R., Calvert, A. (2015), p.754

2.3 Software intensive systems

A Software-intensive system is defined as "…any system where software contributes essential influences to the design, construction, deployment, and evolution of the system as a whole."[108] This applies to the Industry 4.0 and Autonomous Driving fields, as software is an integral part in both domains. As the concept of Industry 4.0 is also called the Internet of Things or even the Internet of Everything, it's a vivid example of a whole world of systems, systems of systems, applications, product families and entire corporations where software is of critical importance. Since the term Industry 4.0 has its origin in Germany's manufacturing sector, and one can see self-driving cars and ultimately Autonomous Driving as a subset of it, this offers a second, more concrete, application example.[109] The automotive industry makes up a large proportion of the manufacturing sector in Germany, and autonomous driving as a cyber-physical system is representative of Industry 4.0.

While both topics are vast and certainly not all connections with software can be captured here, the following chapter provides an introduction and a reference of some general indications and characteristics of Industry 4.0 and Autonomous Driving. Some challenges, as well as existing and future requirements generally related to software will be outlined in preparation for the third chapter with several concrete examples.

2.3.1 Introduction to Industry 4.0

Even though Germany, Europe's strongest economy, has been at the forefront of industrial innovation for decades, it is struggling to adapt to the digital age.[110] All the more it's surprising that the term Industry 4.0 has its origin in Germany. "Industry 4.0 is a German-government-sponsored vision for advanced manufacturing."[111] "In the United States and the English-speaking world more generally, some .. [people] also use the terms the 'internet of things', the 'internet of everything' or the 'industrial internet'."[112] GE (General Electric) coined the name *Industrial Internet* and among others Cisco is credited for using the term *Internet of everything*.[113]

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[108] ISO/IEC/IEEE Std. 42010:2011 (2011), p.4
[109] see Deloitte (2014), p.5, URL see references
[110] see Carrel, P. (2018), URL see references
[111] Kagermann, H. et al. (2013), p.77, URL see references
[112] Deloitte (2014), p.3, URL see references
[113] see Gilchrist, A. (2016), p.1

The term Industry 4.0 also refers to the forth industrial revolution.[114] Same as with SQM, acronyms and terms must be handled carefully. They are used interchangeably, which then leads to misleading definitions. There is no generally accepted understanding of the term, and discussing the subject at an academic level can be difficult.[115] In order to avoid confusion and to provide clarity, the following definition applies:

To roll it down from the top, the term forth industrial revolution relates to a macro-level societal impact with concepts like smart cities, that might not usually classify as industry.[116] Hence Industry 4.0 can be considered as part of the Fourth Industrial Revolution that will be empowered via the Internet of Things (IoT) and the Internet of Services (IoS).[117] Furthermore, Industry 4.0 (as its origin implies) refers to the manufacturing environment specifically, in contrast to all industrial sectors. Consequently, the most consensual synonym for Industry 4.0 is Industrial Internet of Things (IIoT). Industry 4.0 also refers to Big Data, Artificial Intelligence (AI), cognitive computing and other modern technologies that enable real automation with cyber-physical systems (CPS) and ultimately empower dark factories.[118]

The introduction to this work gives examples from Tesla, Uber, Amazon Echo and Apple Watch and associated software quality flaws. Two of the examples belong to Autonomous Driving, which by definition can be assigned to the term Industry 4.0, but also can be seen as a representative of the Fourth Industrial Revolution in general. Amazon Echo and Apple Watch are representatives of IoT consumer products and thus only the end of a manufacturing chain. Nevertheless, these are the initial points of contact for the average consumer to sense the impacts and movements of the digital revolution. As soon as the terminologies are understood, it can make sense to draw conclusions about SQM and Industry 4.0 from consumer products too. A factory manager asking his Amazon Alexa, on his way to work, for the current status report of a dark factory he is responsible for, is just one example of consumer technology and the manufacturing environment blending together. Utilizing smartphones, tablets and smart glasses in factories represents the same idea.[119] Software is the decisive link. Its quality and the management to ensure that are essential.

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[114] see Gilchrist, A. (2016), p.195
[115] see Hermann, M. et al. (2016), p.3928
[116] Marr, B. (2018), URL see references
[117] see Gilchrist, A. (2016), p.195
[118] see Olson, J. (2019), URL see references
[119] see Park, J. (2019), URL see references

2.3.2 Introduction to Autonomous Driving

Autonomous driving exemplifies several topics that have been reviewed at once. "Deploying .. [Autonomous Driving] at scale is a monumental signal data challenge, from safety, driver experience, regulatory, and smart city perspectives."[120] Within the scope of this work we especially investigate Autonomous Driving as a cyber-physical system as opposed to self-driving cars or Autonomous Vehicles. The difference lies in the awareness that autonomous driving is no longer just about the vehicles, even though it is still acting as a proxy at the moment. "Cars with self-driving capability are currently available, with car manufacturers continuing to add this feature to more models each year."[121] Real Autonomous Vehicles and therefore Autonomous Driving continues to be a vision of the future. The distinction is made between the six different automation levels, which are defined by two official institutions. The National Highway Traffic Safety Administration (NHTSA) of the US government and the Society of Automobile Engineers (SAE), an association of automotive manufacturers worldwide. The NHTSA has adopted its standards to the SAE International classification system though, which are described in the J3016 "Levels of Driving Automation" standard as follows:

- **SAE Level 0**
  - Driver is driving, even if his feet are off the pedals and he is not steering, driver must steer, brake, and accelerate to maintain safety
  - Limited support features: providing warnings and momentary assistance, e.g. automatic emergency braking, blind spot and lane departure warning

- **SAE Level 1**
  - Driver is driving, even if his feet are off the pedals and he is not steering, he must steer, brake, and accelerate to maintain safety
  - Selected support features: steering OR brake/acceleration support, e.g. lane centering OR adaptive cruise control

- **SAE Level 2**
  - Driver is driving, even if his feet are off the pedals and he is not steering, he must steer, brake, and accelerate to maintain safety
  - Combined support features: steering AND brake/acceleration support, e.g. lane centering AND adaptive cruise control

[120] Appleby, P. (2019), URL see references
[121] TechPats (2018), URL see references

- **SAE Level 3**
  - Driver is **not** driving, when features are engaged, even when in driver's seat **but** when the feature system requests, the driver must drive.
  - Conditional automated driving features: can drive vehicle under limited conditions but won't operate if they are not met, e.g. traffic jam chauffeur

- **SAE Level 4**
  - Driver is **not** driving, when features are engaged, even when in driver's seat these feature systems won't ever request the driver to take over driving
  - Conditional automated driving features: can drive vehicle under limited conditions won't operate if they are not met,
    e.g. local driverless taxi, pedals/steering wheel don't have to be installed

- **SAE Level 5**
  - Driver is **not** driving, when features are engaged, even when in driver's seat these feature systems won't ever request the driver to take over driving
  - Fully automated driving features: can drive vehicle under all conditions[122]

A vehicle of level 4 and 5 is certainly self-driving, but a self-driving vehicle of level 3 is not autonomous. In fact, the fully automated driving features of level 5 are the point where true Autonomous Driving becomes reality.[123] „An automated car does not have the level of intelligence or independence that an autonomous car has. So driverless and autonomous are nearer to synonyms, as are self-driving and automated."[124] At the current point in time, car manufacturers are stuck with solutions at Level 2. Even in the non-passenger vehicle sector, for example, Daimler presented an autonomous truck in 2014, which already underlines with its name "Future Truck 2025 " that things are not as far as they should be.[125] On Gartner's Hype Cycle for Connected Vehicles and Smart Mobility 2018, autonomous vehicles are already sliding into the trough.[126]
However, this can usually be interpreted positively as the moment when enthusiasm decreases but concrete commercialization or implementation efforts increase. The incidents of Uber and Tesla mentioned at the beginning, the increasing takeover of potential suppliers, ambiguities of the governments in the regulation are only some of the problems that are about to be solved.[127]

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[122] see SAE International (2018), URL see references
[123] see BMW AG (2019a), URL see references
[124] Levinson, D. (2019), URL see references
[125] see Daimler AG (2019), URL see references
[126] see Ramsey, M., Isert, C. (2018), URL see references
[127] see Ramsey, M. (2018), URL see references

2.4 Procedure of the analysis

The three major terms SQM, Industry 4.0 and Autonomous Driving are represented in the popular scientific literature, but seldom brought into relation with each other yet. Therefore, this is a qualitative analysis with explorative character, which is owed to the novelty of connecting these subjects. With the analytical framework an overall understanding and current status of SQM, as well as an outlook for the future was created. In addition, an introduction for Industry 4.0 and Autonomous Driving respectively was made. This provides the conclusive structural basis for a systematic analysis and corresponds to the quality criteria of scientific work. The preceding process of classification, structuring allows the objective evaluation of the prepared subjects and makes their correlation comprehensible and verifiable.

The analysis will bring Industry 4.0 and Autonomous Driving into relation with software and consequently SQM. Furthermore, bringing the three terms in relation to each other enables to answer the research questions and work out requirements for SQM, which are derived from the two examined fields.

For this purpose, a comprehensive document analysis of all publicly available sources that could be reached on Google and YouTube was specially carried out. Tech-Blogs, reports and trend analyses from representative consulting companies as well as web articles were selected as a source of information. In the process, the examples were deliberately chosen in such a way that they provide a general understanding of the representative challenges. Rather, a holistic understanding was considered than too concrete problems within an IIoT software, or surveys on which SQM method is used by a company involved in Industry 4.0. The real-life examples in the analysis are used to underline the assessment of whether or not current approaches meet the new requirements for SQM. The comparison of observations made in the area of SQM with the requirements of Industry 4.0 and Autonomous Driving, as well as the re-examination of the quality definition, will provide an overview of the results of this analysis in chapter 4.

3. Analysis

3.1 SQM in the Industry 4.0

Typical software applications in the manufacturing environment are business management, production management, and control and regulation software.[128] With regard to Autonomous Driving, IBM offers a concrete and tangible example how these applications are referenced to an Industry 4.0 architecture. Figure 6 "... illustrates the dependencies of an IIoT platform from the standpoint of an automotive manufacturing process involving welding, body assembly and painting equipment lines. It could be translated to other manufacturing processes and most concepts stay relevant."[129]

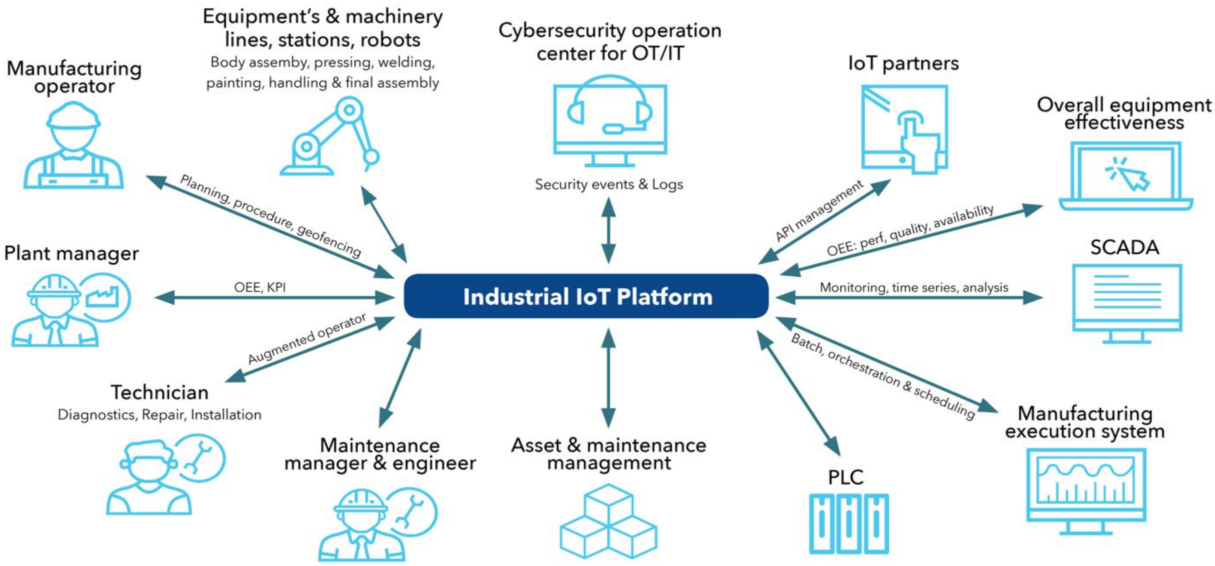

Figure 6 - IIoT Platform, according to IBM (2018), p.12

To understand of the scope and detail in which everything can be linked in manufacturing, an interesting example are bolts and nuts equipped with structural stress sensors that can deliver data about slight stress-related changes and shifts around them. Such sensors can form so-called sensor webs and enable live and streaming data of virtually any type that is needed, from any part of the physical world in which they are being built in. [130] It should not be confused that more simplistic software problems, such as a wrong movement of a cobot (a robot designed to interact physically with humans) belong rather to the third industrial revolution. Modern software issues relate more to data and more importantly to analyses. That is what will change the way machines, processes, products and our operations are perceived.[131]

[128] Kagermann, H. et al. (2013), p.40, URL see references
[129] Bonnaud, S. & Didier, C. (2018), p.12, URL see references
[130] see Virtual Worldlets Network (2014), URL see references
[131] see Bonnaud, S. & Didier, C. (2018), p.10, URL see references

The McKinsey 2018 Digital Manufacturing Global Expert Survey shows that one of the highest priorities for many industrial companies worldwide is digitizing the production value chain. The three areas in which they actively pursue solutions are connectivity, intelligence, flexible automation.[132] In detail this includes the following:

- **Connectivity:**
  examples include digital performance development and the use of augmented reality to communicate interactive work instructions. The focus lies on enabling the flow of relevant information to the right people in real time

- **Intelligence:**
  examples include predictive maintenance and AI-driven demand forecasting. That means applying advanced analytics to an array of data to generate new insights and enable better decision making

- **Automation:**
  Examples include autonomous guided vehicles and using cobots for assembly processes. That translates to the utilization of new robotic technologies to optimize productivity, quality and safety of work processes[133]

Two observations can be made here. First, it is about the increasingly complex interconnection of the physical (hardware) and virtual world (software). Secondly, it is about the meaningful use of the resulting data streams. A major bottleneck is that most companies fail with the analysis and generate no value from the collected data.[134] "Manufacturing companies should drive execution of their Digital Manufacturing initiatives with an agile mindset across software and analytics."[135] Many companies do not look for solutions for operational weak points nor do they want to create competitive advantages, rather to find exciting solutions for which no problem exists.[136] Just as with SQM, the trend that validation must come before verification and that end-user orientation is a major issue is also evident here. For Industry 4.0 and digital manufacturing, the development of software, in other words the SDLC, must be

[132] see McKinsey (2018), p.6, URL see references
[133] see Schmitz, C., URL see references
[134] see Henke, N. et al. (2016), URL see references
[135] McKinsey (2018a), p.15, URL see references
[136] see Schmitz, C., URL see references

paralleled by the development of the IIoT Platform and its connected components. “Value emerges as a combination of the tool and the people who use it.”[137] The same was described for the definition of SQ. The quality of competence development, training and documentation is an essential part of SQM in Industry 4.0. "The growing use of software, connectivity, and analytics will increase the demand for employees with competencies in software development and IT technologies, such as mechatronics experts with software skills."[138] In the coming years, as Industry 4.0 fully matures, countless new software vendors will be fighting a first mover battle.

SQM processes must meet the requirements for reliable and uninterrupted operation. Especially in cases in which safety or life of people is endangered by software failure, organizations not only risk their brand value, but their very existence. In the SDLC that has been common until now, software is usually delivered in a version 1.0 and in subsequent releases bugs are fixed and functions that were missing are added. Despite all completeness of tests, there is still a quality gap between the first release of the product and the time when the market considers the product to be of high quality.[139] "Minimizing or eliminating this quality deficit should be high on the priority list of every organization that is building software."[140]

As described in the previous chapters, SQM methodologies face the challenge of balancing agility, accelerating time-to-market, and simultaneously delivering high-quality software. It has been established that the future of SQM will depend on a better and, above all, more integrated role of testing, especially UAT, in the SDLC. Separate testing teams, as it is currently often the case, cannot be the answer to software systems that need to function properly the first time the delivery is made and that can be fully relied upon. "The solution is to treat test cases as a valuable asset of the organization, and leverage them across the entire team and application life cycle."[141]

A recent report by the Boston consulting group on seven forces that will reshape enterprise software lists areas in line with what has been outlined so far and also named for SQM. The listed forces and some key takeaways of the report are as follows:

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[137] Schmitz, C., URL see references
[138] Gerbert, P. et al (2015), URL see references
[139] see Paliotta, J. (2015), URL see references
[140] Ibid.
[141] Ibid.

1. **Big Investments**: industry investment increased in Cybersecurity and AI a.o.
2. **Cloud 2.0**: Cloud-Native Connectivity of everything, APIs are more important
3. **AI Pioneers**: Twin turbines of AI and Big Data will take up ~40% of spending on digital transformation initiatives in 2019
4. **End-User Power** more digital native millennials in B2B roles, having a better eye for software → higher requirements to quality in the industry
5. **Data Protection**: privacy concerns, stronger data policies and enforcement, although three-quarters of breaches are caused by human, process, or organizational errors rather than by inadequate security technology
6. **Preferred Platforms:** superplatforms (platforms of platforms, e.g. Microsoft Azure, Amazon AWS) → mass adoption of controlling systems of machines
7. **Hiring Hell**: talent shortage, demand of employees with software skills[142]

Two of these factors are backed up by a quality report from the official publication magazine of the American Society for Quality, which lists 2019 latest manufacturing trends. Their report calls them data management (twin turbines AI and Big Data) and training (hiring hell). Again, it is about the massive accumulation of data in Industry 4.0 and its management and value creation, just like the parallels of documentation in SQM (software is only as good as the user who uses it) and the training associated with the growing demand for software-competent specialists.

In addition to the listing of the seven forces, the reference of the BCG report to DevSecOps is worth mentioning. DevSecOps is sort of a derivative of DevOps, which was mentioned earlier, but was not explained in detail. DevOps is a set of practices that combine software development (Dev) and information technology operations (Ops). "… software developers are building better protective protocols into every stage of application development. DevSecOps prevention, detection, and responsive security processes and controls are applied across a product's life cycle to reduce the time needed to identify and remediate threats and vulnerabilities."[143] Since security is considered one of the major software quality concerns for Industry 4.0, this is a particularly interesting approach for SQM.

With the interconnected nature of Industry 4.0 cyber-attacks could be as devastating as disabling a whole nation's infrastructure as pictured in the 2007 fourth part of the

[142] see Iyer, S. et al. (2018), URL see references
[143] Ibid.

Die Hard film series with Bruce Willis (which is - funny enough - released with the title Die Hard 4.0 outside of North America).[144] “In our hyper-connected world, IT security covers not just our data but virtually everything that moves - including machinery. Cyber-attacks or IT malfunctions in manufacturing can pose risks to the safety measures in place, thus having an impact on production and people.”[145] For now, even Amazon, using 800 automated robots in one of their warehouses, still employs humans to babysit their robots.[146] From an SQM perspective IoT device manufacturers need to incorporate secure coding practices and incorporating cybersecurity leading practices right from the start of the development life cycle.[147] Secure software development life cycle (S-SDLC) can be considered a DevSecOps process, adding security-related activities to an existing development process (SDLC).[148] "For example, writing security requirements alongside the collection of functional requirements, or performing an architecture risk analysis during the design phase of the SDLC."[149]

Similar to the futuristic testing processes for SQM specified in chapter 2.2.2 there have been attempts (see Cyber Grand Challenge) to create AI platforms that can scan networks and identify software vulnerabilities, and apply patches without human intervention. The Defense Advanced Research Projects Agency (DARPA) foresees reducing cyber security risks through AI platforms, which can significantly reduce the time humans take to identify weak points and also develop patches for them in or near real time.[150] “[The]… use of AI to power real-time responses to threats may be critical in moving forward with a secure, vigilant, and resilient approach to Industry 4.0 - enabled devices.”[151]

It turns out that the same technological drivers that empower Industry 4.0 are the ones that enable SQ to meet the corresponding requirements. Namely, the accumulation of data, its analysis and the subsequent translation to cognitive computing and artificial intelligent systems, that help to deliver perfect software quality at the first attempt.

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[144] see IMDB (2007), URL see references
[145] Naden, C. (2019), URL see references
[146] see Ackerman, E. (2019), URL see references
[147] see Waslo, R. et al. (2017), URL see references
[148] see Mougoue, E. (2017), URL see references
[149] Ibid.
[150] see Faggella, D. (2019), URL see references
[151] Waslo, R. et al. (2017), URL see references

3.2 SQM in Autonomous Driving

The initial hype about Autonomous Driving has finally been transferred to a clear objective for companies, and all sorts of industries have entered the competition. Undoubtedly, Tesla and their autopilot system have triggered a lot of hype about driver assistants and automated driving in the last few years. On their website, they clearly state that the autopilot system in its current form is not an Autonomous Driving system and is currently classified as a level 2 automated system.[152] BMW also announces that the current systems meet level 2 standards and that systems for level 3 in mass production are currently under development.[153] While Daimler AG and the BMW Group are launching their cooperation on automated driving and claim that solutions up to SAE Level 4 will be available to private customers from 2024[154], Ford[155] and Volvo[156] are already rethinking Level 3 autonomy after declaring that they intended to move straight to Level 4. Audi recently released the A8 sedan, the world's first autonomous level 3 vehicle in series production, and failed only due to a lack of government regulations to officially get level 3 status.[157] "Combine consumer acceptance with cost, uncertain regulatory landscapes with the thorny nature of control exchanges and driver monitoring, and Level 3 remains an elusive goal."[158]

With points 4. (freedom of risk) and 5. (context coverage) of the ISO definition of software quality in use in mind, software quality management in Autonomous Driving will also be about rethinking the user interfaces already in use. Tesla has recently released a video that shows how close their autopilot gets level 5 full self-driving capabilities. However, some drivers may have too much confidence in current systems, such that a man has already been caught twice sleeping while driving[159], and a couple even shot a porn film in a Tesla while driving.[160] Modern software systems must be designed in such a way that the passengers are unmistakably informed how much attention they have to pay. The complexity of situations where the vehicle needs to handover to the passengers is the reason why many want to skip the SAE Level 3 chasm. For SQM difficulties in documentation, End-User Focus and UAT are revealed.

[152] see Tesla (2019), URL see references
[153] see BMW AG (2019b), URL see references
[154] see Mercedes Benz (2019b), URL see references
[155] see Martinez, M. (2019), URL see references
[156] see Auto2xTech (2019), URL see references
[157] see Wasef, B. (2018), URL see references
[158] see Bigelow, P. (2019), URL see references
[159] see Loeffler, J. (2019), URL see references
[160] see Dodgson, L. (2019), URL see references

And while it seems that a lot of traditional car manufacturers are catching up and taking advantage of already existing massive production facilities, economies of scale to be competitive in price and hire enough people to become good at software, there are a few other aspects to consider.
Surely Tesla’s CEO Elon Musk is a special personality, and a company with start-up and underdog status has to keep the shareholders entertained with many compelling announcements. However, Tesla actually moves along the cutting edge and is the company which pushes the limits in both hardware and software that are necessary for autonomous driving. While BMW, for example, actually still asks customers to transfer software updates via USB stick and offer their first over-the-air update only for selected models[161], Tesla has long shown that over-the-air software updates based on an Apple-Esque principle turn cars into platforms.[162]
Tesla's philosophy seeing themselves as a Silicon Valley software company offers above all the right perspective for an automobile in the orbit of autonomous driving and, associated with this, the reference for software and SQM.[163] The actual vehicle becomes less important and software plays a key role. Currently, software requirements include the implementation of safety and driving assistants, a sleek and intuitive UI, and Connected-Car features. Companies such as Apple and Google are penetrating the market and pushing their solutions into the vehicles of classic manufacturers such as BMW, Mercedes, Audi, Ford and many more. Although Connected-Car should not be confused with Autonomous Driving, the connectivity part shows an effect of standardization and homogenization that is typical for software. At the moment it is still about the integration of vehicles into established software like Microsoft Office, Android and Apple's iOS operating system (one could argue that it is the other way around, that these systems get integrated into vehicles, but it is clearly not). In the future software quality managers will have to deal with standards and regulatory compliance to control systems for different vehicle types and city districts. This is not only the drastic impact of the Fourth Industrial Revolution that is evident, but also the transformation from a Big Data to an Extreme Data economy.[164]
Since owners have already driven one billion miles with autopilot activated, Tesla's advantage could lie in the gathered data they can learn from.[165] Waymo, formerly

[161] see BMW AG (2019c), URL see references
[162] see Szymkowski, S. (2018), URL see references
[163] see Jerry, H. (2015), URL see references
[164] see Negahban, N. (2019), URL see references
[165] see Lambert, F. (2019, URL see references

Google's self-driving car project, has also covered eight million miles on public roads with its Autonomous Vehicles and works on building an AI-based self-driving system. Interestingly enough, the company has also *driven* more than five billion miles in simulations over the past nine years.[166] BMW even says on the company's own website that test vehicles are not able to gather all the data necessary on the real road and that therefore 95% of all test miles are driven virtually.[167]

Like Waymo, the software companies Cruise Automation, Zoox, Apple, Aptiv, May Mobility, Pronto.ai, Aurora, Nuro, the Russian company Yandex and, of course, Uber focus on Mobility-as-a-Service (MaaS) especially with Autonomous Driving as the foundation for their service platforms.[168] As already mentioned above, the Shared Economy will have a big influence on future SQM measures, since everything from the security of the vehicles to the simplicity and flexibility of the applications for booking different services depends decisively on the software quality. Perhaps one of the most interesting things will be what Apple and Ford do, as the CEOs of both companies agree that one of the most important projects is the AI for future operation systems and platforms for autonomous driving. While Ford has acquired a company that wants to build "… a kind of iOS for cities, managing data and transactions…"[169], "the thing about being a platform that connects the world is that others have to agree to come aboard."[170] And that's where Apple has a proven track record of developing high-quality software that people and businesses can trust and enjoy adapting to.

Another interesting aspect for software quality management is that the performance of future AI systems might become an essential factor. With their upcoming hardware update Tesla will achieve a tremendous performance boost through performing necessary AI calculations on a bare metal level, that means without the use of software emulation. The autopilot cameras will be able to record and calculate 2000 frames per second.[171] The interesting aspect here is that one can speak of a software reduction (or lean software), since even modern high-performance chips cannot handle the enormous amounts of data if there are too many intermediate stages of software. This increase in the requirements on performance, emphasizes the high complexity of Autonomous Driving, as an offspring of Industry 4.0 reaching into the consumer world.

166 see Korosec, K. (2018), URL see references
167 see BMW AG (2019b), URL see references
168 see Price, R. (2019), URL see references
169 Marshall, A. (2019), URL see references
170 Ibid.
171 see Stumpf, R. (2018), URL see references

4. Results & recommendations

The results and thus the answers to the second and third research questions will be shown in two steps. In subsection 4.1, the results of the analysis from chapter 3 will be outlined and accordingly clearly summarized in Table 3. It will be answered whether or not current SQM methods fulfill the requirements of Industry 4.0 and Autonomous Driving. Subsection 4.2 answers the question of whether a new understanding of SQM can be derived from the gained insights of this work.

4.1 Fulfillment of requirements

Due to its high complexity, Table 3 is only partially self-explanatory, and requires the understanding of all this work. The findings on the status quo in SQM (left column) are compared with the major factors and key requirements in Industry 4.0 and Autonomous Driving (right column). Only new discoveries are listed and facts considered redundant, e.g. the indispensable role of agile methods or other established matters are not.
In the center of the table the connecting links of requirements and SQM approaches are listed in three categories. Even if actually everything is connected in such a way that an interlocking class diagram would theoretically be more accurate, this tabular categorization offers an equitable and comprehensible representation of the results. The positions marked in green are those where requirements are clearly fulfilled, the positions marked in orange are considered to be only partially fulfilled and the critical points where requirements are not considered to be fulfilled are marked in red.
Proceeding from top to bottom, the methods of using hybrid models, using simulations and visualizations, implementing Crowdtesting and secure software development can certainly be taken for granted. The associated requirements of better documentation and training, better validation of needs, better use of existing information, as well as the approach of Autonomous Driving in the sense of shared services and the consideration of security factors can be fulfilled in any event at present. However, it is still up to the SQ managers to take these requirements first and execute implementations. In the middle part, the discussed examples of ISO standards provide reason to believe that future SQ managers will think larger and adapt their software to industry standards to make IIoT platforms as versatile as possible. Experience has shown that government regulatory work will become a big obstacle for Autonomous Driving platforms and the prospect of internationally accepted platforms is low, but possible from a software point of view, although not yet. In the last and thus lower third

the concepts in the area of SQM are listed, which can currently still be described as rather futuristic. Of course, current Artificial Intelligence systems are already very mature, but not yet on such a scalable level that the proposed approaches can be fully implemented and software versions 1.0 would be completely error-free. At the moment there are also expensive Big Data analysis systems with AI in use, but the requirements for software, its performance as a quality factor and the overall quality are not yet geared to the extreme data analysis that will be necessary in the near future. In conclusion, it must be said that the requirements of Industry 4.0 and Autonomous Driving for current SQM are only partially met and a parallel evolution is taking place. Sometimes solutions are ahead of requirements, in other cases the other way around. The current definition of software quality, however, still covers all aspects and simply has to improve in practically all characteristics.

SQM new methods, standards or concepts		Requirements Industry 4.0	Autonomous Driving
METHODS			
Hybrid-Methods Combination of heavy- and lightweight methods (e.g. AZ-Model)	**End-User Focus & Validation** What do users really want and need	**Documentation & Training** Workforce with software skills	People must understand the AVs
Simulations & Visualization www.irise.com and www.invisionapp.com		**Validation** Don't use fancy tech without a usecase for it	
Crowdtesting Real human end users test drive the software | www.usertesting.com		**Meaningful use of data streams** Enable the flow of relevant information	**Shared Economy** Rethink AVs with MaaS, TaaS
DevSecOps & S-SDLC Risk management for cyber-attacks found their way into the SDLC		**Safety & Security** Cyber-Security for machines	Rethinking of User Interfaces
STANDARDS			
ISO/IEC 25010:2011 The defitinition still applies and covers all aspects	**Standardization and Homogenization**	**Platforms that connect the world** IIoT Platforms	Autonomous Driving Platforms
ISO/IEC/IEEE 90003:2018 and IWA 27 Prime examples that more standards will be considered part of SQM		**API standards** IIoT needs to work together probertly	**Uncertain regulatory landscapes** Governments, Cities, Communities
ISO/IEC 27001 Example for higher focus on information security in particular			
CONCEPTS			
Built-In UAT Infuse end user at the front of the SDLC (see AZ-Model)	**Reduce the version 1.0 to 2.0 gap** • AI as answer for everything • getting it right the first time	**BigData → Extreme Data + its Analytics** create real value from the data collected	
Mimic real end product / real end user Augmented Reality, Cognitive Computing and Artificial Intelligence		**Better decision making** Create insights through data analytics	**Virtual Testing** Close to real world scenarios via AI
Fully automated user testing systems Autonomous AI systems that use neural networks		**Automated Cyber-Security** Find and close loopholes through AI	**Leaner Software** Need to improve the performance for AI
Cognitive Computing Chips Chips inside humans to gather better data to built AIs			

Table 3 - Results of the analysis

4.2 The new understanding of SQM

With the answer to the third research question, whether a new understanding of software quality management has emerged, the answer to the fulfillment of requirements is also rounded off. No official new SQM method was truly identified, except that new combinations are being used and hybrid models are emerging. If automated testing as described above actually becomes a reality, one could even predict a certain backward trend towards more streamlined procedures in Software Development. More important, however, is the fact that aspects that have so far been dealt with separately and have only indirectly belonged to SQM will be implemented more strongly. Topics such as security and risk management, but also regulations compliance especially with software, as well as the immensely underestimated role of a genuinely adequate UI, will be seen as part of software quality. The repeatedly mentioned higher end-user can be seen as the premise here. Not without reason the ISO has separate standards for different topics. The example of the guidelines for Shared Economy was given, and due to the ever more intertwining influences of software, the understanding of software quality could redefine itself. The factor that software is only as good as the person who uses it will also play a greater role. On the basis of how new employees are trained, as well as on how managers and end customers use the full extent of functionality of their software, it will be measured that documentation, training and much better UIs will be incorporated into the new understanding of SQM.

To conclusively answer the question of whether the requirements are met, it must be added that it is up to managers to expand their understanding of software quality accordingly and create an appropriate culture in their organizations and teams, as well as build and create understanding among customers.[172] In the last decade, in the course of agile development methods, it was already sufficiently propagated that an agile corporate culture or a culture of quality should be lived. This has to be put into practice at the latest now. In years to come, the focus might shift back to the end product rather than the process. There may not necessarily be a new understanding in the sense of defining software quality management, but certainly the new situation will reconfigure the perspective of SQM significantly. Both for the end customer and within organizations, SQM will play an increasingly important role in the coming years. When everything is about software, QM in general will be more about SQM.

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[172] see Das, L. et al. (2017), URL see references

5. Discussion and controversies

5.1 If it's convenient and fancy we don't mind the risk

In the introduction, the need for higher quality software was highlighted with examples from Tesla, Uber and Apple Watch. In the course of this study, the example of implanted chips in the hands of employees was mentioned, as well as the cyber-attack risks in the industry and the high security risks associated with the misuse of the not yet truly autonomous autopilot functions.

The problem of sharing private information is nothing new, and people definitely know about it - and they do it anyway. In mid-2018, the General Data Protection Regulation (GDPR) was enforced in Europe.[173] Data and how it can be shared has changed dramatically, especially for software companies, and has created a huge number of new terms of services, alerts in apps and websites, reports and lawsuits worldwide. For example, Facebook has paid $5 billion penalty over privacy breaches this year, which is certainly a step toward raising awareness about the value and importance of data security in the private sector.[174] The collective knowledge about social networks, apps, search engines, however, may be bigger than it is the case with Smart Watches (e.g. health data, location history), smart home products (data about open door, lighting, cameras, door-locks), and many other things of the IoT world. "Alexa and Google Assistant have achieved critical mass and, despite some security and privacy concerns, are increasingly integrated into how we operate things in our homes."[175] What is trendy and practical is bought and used.

Where do *freedom of risk* and *security* as quality criteria begin and where do they end, and does it simply have to do with common sense? „Gartner research shows that an increasing number of consumers would trade convenience for the assurance of data privacy."[176] Instructions or warnings are usually not read by users just as they are not reading terms and conditions. It is unfortunate that convenience goes beyond quality until the awakening happens due to deaths caused by software failures in semi-autonomous cars. One of Elon Musk's more recent companies is working on chips that will be transplanted into the brain to create a brain-machine interface (BMI) in order to treat neurological disorders (e.g. Parkinson's disease) using AI.[177] The additional opportunities for human-machine interaction in industry are as great and useful as they

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[173] see Brandom, R. (2018), URL see references
[174] see Nuñez, M. (2019), URL see references
[175] Lamarre, E., May, B. (2019), URL see references
[176] Blum, K. (2019), URL see references
[177] see The Economist (2019), URL see references

are frightening and potentially risky for others. The gap between visionaries and conservatives could widen in the coming years amongst consumers as well as company leaders. A mindset shift must take place both in society and in industry, since many of the problems described are only just the beginning and will really become scaled as platforms (e.g. IoT-, IIoT-, Maas-, TaaS-, AD-, Smart Health-, Smart City-Platforms) emerge. "Society is adjusting, adapting and reacting and trying to advance what we have to work with and to live with."[178]

From an industry perspective, in terms of practicability, the factor that companies opt for solutions that ultimately do not provide real value although they are supposedly convenient comes into play again. Companies not only risk their sensitive data and the safety of employees in modern factories, but also unnecessarily high costs. SQ managers who work for a company that develops software products (e.g. IoT platforms) need to confirm what their customers really need to develop better software. But manufacturers also need to determine what software technology they need to solve production problems rather than trying to gain momentum in the race for Industry 4.0. The principle of *new features pay better than a bug-fixed version* is basically less valid in the B2B area than in the B2C area. The attention of B2B buyers is usually completely different from that of an end consumer, and risks and costs are carefully weighed up. But with the transition into Industry 4.0 things are a little different. A KPMG research has shown that some executives suggested that Industry 4.0 could be a potential competitive differentiator to position their company as a *cool* place to work, especially for millennials.[179] The future of the industry in all areas will essentially depend on software quality and, as repeatedly mentioned, mainly on the utilization of data obtained from sensors. The time for experiments is over both for software developers and their users in industry and the consumer sector. It is important to be bold and strategic and put value and performance first instead of technology to recognize the possibilities.[180] In a certain way it even makes sense to not mind the risks, but not at the price of SW quality in the sense of convenience, but quality in the sense of stability, value enhancement and real benefit. "Amid the dramatic changes engulfing every sector, few leaders appear willing - or prepared - to pursue bold steps instead of narrow initiatives."[181]

[178] Zukis, B. (2019), URL see references
[179] KPMG (2017), URL see references
[180] see Harris, P. et al. (2018), p.26, URL see references
[181] Ibid., p.26

5.2 Trust and leadership is key in the 4th industrial revolution

Following the previous chapter, one can refer to the old definition of quality mentioned at the beginning of chapter 2.1 in the sense of the user-based approach of D. Garvin: "A consumer may enjoy a particular brand because of its unusual taste or features, yet may still regard some other brand as being of higher quality."[182] This old definition underlines that people are not paying attention to what they actually need or want, but only to what they think they want and what appeals faster and better. It will take the right leaders to build brand trust, which is a major challenge for tech companies.

It can be assumed that certain topics such as data security and safety for the body, mind and soul of people will be more strongly integrated into newer definitions of software quality. In a world where software increasingly controls devices and machines and supposedly gives them human-like capacities (e.g. humanoid robots by Boston Dynamics, Honda, Hanson), quality will also mean that these systems can be trusted. Companies can make a name for themselves by standing for quality in terms of reliability in handling personal data, money, vehicles, and other areas of people's lives. With Apple it has long been established that it is not about their iPhones and iPads, but about platforms and services. We have translated this to Autonomous Driving and Industry 4.0, which will also be about the ecosystems and platforms around it. Since Apple is now competing in streaming and digital payment services against a generation of tech companies that sell ads and gather and distribute massive amounts of personal data, it can be said that online services compete on trust, and Apple is pitching itself as a privacy provider.[183] Apple's CEO Tim Cook recently used a quarter of his commencement speech at Stanford to address these issues and to prepare the new generation of Silicon Valley leaders that responsibility also means thinking things through.[184] Between technology giants like Facebook, Google and Microsoft, the battle for the title of best data protector has already begun.[185] The described problem of trust in certain platforms from the private sector is in principle nothing new for the industry, since platforms and clouds are already in use here as well. However, the scale is not the same yet and as it will increase dramatically, the trust building described here could become exemplary for the Fourth Industrial Revolution and "success on the transformation journey demands informed CEOs navigating precise roadmaps."[186]

[182] see Garvin A. D. (1984), p.27
[183] see Brandom, R. (2019), URL see references
[184] see Tim Cook (2019), URL see references
[185] see Wong, J.C. (2019), URL see references
[186] Harris, P. et al. (2018), p.6, URL see references

5.3 Critical appraisal

At various points in this work, complications can be identified; hence a critical appraisal should reflect them and conclude the discussion. First, despite clear inclusion and exclusion criteria, one of the major challenges was to create a seamless research framework. An important part of this work is to close the research gap on the current state of SQM, which in turn means that there were few sources that were really up to date. Especially the hierarchical structure as well as clear definitions and differentiation of terms like SQM, SQA, SQC etc. made this difficult. Furthermore, there is a careless handling of descriptions of what is a method, a framework, a process and whether it refers to a project or a management procedure or to programming in particular. These challenges have been overcome to the greatest extent possible.

Next, alongside these diffuse terms, some of the evidence led in the direction of testing, risk and security, which in a certain sense belong to SQM, but are also separate issues. Within the scope of this work, efforts were made to highlight the associated quality characteristics and reference points relevant for SQM without unnecessarily confusing separate subjects.

Another possible point of criticism consists of two factors. On the one hand, a certain basic knowledge is required to fully understand the results, since many terms such as SCRUM or CMMI, for example, are not dealt with in depth. In addition, a considerable gap also arose due to a lack of information. In particular, this means for the first part (see chapter 2.1 and 2.2) that only indirect information could be obtained about the exact methods currently used by companies working in the two fields studied. Concrete surveys and reports from trade journals, congresses, blogs and consultant reports mainly offered examples of the requirements in Industry 4.0 and AD, but little about the term SQM. This leads to the conclusion that SQM has not been in the spotlight enough in recent years, or that the above-mentioned blending of the terms SQM, SQA etc. is responsible. Due to these two factors, it could be claimed that especially the first research question has been answered only vaguely. With the exception of the AZ method, no precise new method or the best procedure could be pinpointed. Future empirical work may be able to provide more concrete answers.

In conclusion, it can be said that the scope of this work was limited and only scratched the surface of these three major topics SQM, Industry 4.0 and AD. However, with the outlined concepts clear indicators of compliance are presented and correlations are established. In fact, an introduction and a first step for further investigations is offered.

6. Conclusion and outlook

There is no doubt left that SQM will be one of the most important topics for all businesses in the upcoming years. In order to emphasize this fact, this work focuses on the understanding of what SQM actually is, presents the status quo with current methods, standards and concepts, and then relates this to two very interesting fields of investigation. Requirements on SQM in the field of Industry 4.0 are particularly interesting for the business perspective and Autonomous Driving as a second field of investigation offers new insights as a link between the industry and private individuals.

This work has clearly shown that there are indeed new concepts that have been developed in recent years. In the form of hybrid approaches in development, the use of cognitive computing and AI for extensive UAT and the notion of a representative example given by the AZ model for new developments of methods, several new concepts have been identified. The actuality and coverage of standards in relation to software quality was confirmed and complemented by considerations to add further standards to the SQM area that were previously not related to this subject. The question whether the requirements of Industry 4.0 and Autonomous Driving can be met is answered in detail with the table in chapter 4. One can speak of a partial fulfillment, since some methods already exist and it depends in each individual case on the executives to apply them.

In the first of three identified fields, namely End-User Focus and Validation, Autonomous Driving is rethought in terms of Shared Services. Safety and Security challenges can be met (if implemented). However, there are still distinct problems in validating the right user needs and making meaningful use of gathered data. In the second field, standardization and homogenization, requirements are already addressed in the form of IoT platforms. Platforms for Autonomous Driving are under development, and obvious shortcomings still remain in defined regulatory landscapes. The third field, in which futuristic methods, especially based on AI, are intended to improve quality as a whole, cannot be regarded as a fulfilled area. However, it was precisely these positive outlooks that led to the answer of the third research question. It has shown very clearly a new understanding of SQM and a necessary mind shift in end-users and developers. The objective of the work was accomplished and was complemented by the subsequent discussion.

It will depend on the right leaders which concepts become reality, and in which areas collective knowledge grows. However, SQM in any case will become both deeper and broader, since more and more areas will flow into the new understanding of quality.
This work provides the basis for many different subsequent studies. Especially with regard to the difficulties with the different terminology, research is needed to unify the many perspectives on SQM, SQA, SQC, SQP, SPI, Testing, Risk Management, Assessment, Assurance, etc. in order to avoid additional confusion and further *abuse*. Empirical studies on the concrete implementation of SQM in certain companies could be just as interesting as concentrating on certain quality aspects such as UI design as major quality characteristic and the associated effects.

In conclusion, it must be said that this work in itself represents exactly what was found as a result: explanations, futuristic prospects and the up-to-dateness of the subjects, are put into relation and provide a good guideline for actors in the ecosystems discussed. The identified weak spots in Industry 4.0 and Autonomous Driving with regard to management in software quality could, in addition to the field of research, also represent relevant directions in practice. After all, only through a holistic understanding and an extended view, the quality of software in all its dimensions will develop to such an extent that it not only meets the requirements of Industry 4.0 and Autonomous Driving, but also provides the decisive solutions to move technology and people forward.

Appendix

QUALITY IMPROVEMENT METHODOLOGY

NON-IT RELATED

QIM	VALUES	INITIAL COST AND DURATION	APPROACH / TOOLS AND TECHNIQUES	WORK CULTURE	INFO SUPPORT	SUCCESS STORIES	
TQM	**Organizational Performance,** Not a "quick fix", Customer Satisfaction, Continuous Improvement	**COST:** Level 4 **DURATION:** 1-3 years	Analytical tools, Statistical tools, "Seven Quality Control Tools", "Seven Management Tools"	To change corporate cultures from a passive and defensive culture to a proactive and open culture	Training, Workshops (Customised and Public)	Ford, Motorola, Toyota, Pentel, Canon	QUALITY ASSURANCE
ISO	**International standards ensuring quality in products & Services,** Operational Performance, Customer Satisfaction, Improved Employee Morale	**COST:** Level 3 **DURATION:** 3 months - 2 years	Application of statistical methods Measurement methods and results Evaluation of conformity	Top management, First line management	SIRIM DAS DQA	GSK, Universal Foods Ltd, Sime Darby, Colgate	QUALITY ASSURANCE AND QUALITY CONTROL
LEAN MANUFACTURING	**Maximize customer value** & minimize waste, Less Variation and input, Uniform Output	**COST:** Level 2 **DURATION:** Min. of 10 weeks	Understand customer value, Value Stream Analysis, Improve activity flow without interruption, Customer Pull & Perfect the process	Operational Level / Executive Level and Top Management Level	Lean Enterprise Institute (LEI) Workbook Set, seminar, conferences, forum & online training	Intel, TESCO PSC, Nike, Honda, Boeing	QUALITY ASSURANCE AND QUALITY CONTROL
SIX SIGMA	**Quality at near perfection,** Less Waste, Less Throughput Time, Less Inventory	**COST:** Level 1 **DURATION:** 1-3 years	Process Improvement DMAIC (Define, Measure, Analyse, Improve & Control) New Process DFSS (Design for Six Sigma)	Lead by Black / Yellow / Green / White Belt Confine to operational level to top management in the organization	Six Sigma training and certification firm	Chevron, General Electric, HSBC Group, Honeywell, United States Air Force	QUALITY ASSURANCE AND QUALITY CONTROL

IT RELATED

	VALUES	QIM	INITIAL COST AND DURATION	APPROACH / TOOLS AND TECHNIQUES	WORK CULTURE	INFO SUPPORT	SUCCESS STORIES
QUALITY ASSURANCE	**IT Best Practices and Quality Framework,** Improves ROI, Improves Productivity for Business and IT Staff	ITIL	**COST:** Level 4 **DURATION:** 3-10 months	Framework for the governance of IT Service Management, Process-Model Software	Top Management and Project Team	ITIL Official website, Info-Trek	NASA, Disney, Microsoft, IBM, Telefonica
QUALITY ASSURANCE AND QUALITY CONTROL	**International Standards for Quality in IT Process, Product and Services,** Customer Satisfaction, Improved Employees Morale	ISO	**COST:** Level 3 **DURATION:** 6 months - 2 years	Software Change Control Management	QMS compliance and conformity is part of KPI for all project team members	SIRIM DAS DQA, ISO Institution	Hewlett Packard, Din Micro Systems, ANSA Tech., Philips
QUALITY ASSURANCE AND QUALITY CONTROL	**Evaluating and Improving the way software is built and maintained,** Continuous Improvement, Customer Satisfaction	CMM / CMM-I	**COST:** Level 2 **DURATION:** 1-5 years	CMM-I 3rd party tools and services	QMS compliance and conformity is part of KPI for all project team members	CMM-I Institution: comprising of CMM-I Models, Advisory Groups, Product Teams, Conference	Hewlett Packard, Citicorp, IBM, Motorola, Siemens
QUALITY ASSURANCE AND QUALITY CONTROL	**Quality between 2-4 Sigma,** Less Waste, Process Efficiency, Improved IT Services and Client Satisfaction	SIX SIGMA	**COST:** Level 1 **DURATION:** 1-3 years	Advanced statistical tools, Analytical tools, Supporting software, Represented a well contained packaged set of tools that can be used to measure and analyze manufacturing process variability and implement some form of process control	Lead by Black / Yellow / Green / White Belt Confine to every level in the organization	Company in-house adoption of Six Sigma Black Belt	Dell, Samsung, Xerox, Siemens, Vodafone

Table 4 - QIM Roadmap, according to Wong, W.Y. et al. (2018), p.156

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