Development of a Model to Evaluate the Potential of 5G Technology for Latency-Critical Applications in Production

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***Abstract*—Latency-critical applications in production promise to be essential enablers for performance improvement in production. However, they require the right and often wireless communication system. 5G technology appears to be an effective way to achieve communication system for these applications. Its estimated economic benefit on production gross domestic product is immense ($740 billion Euro until 2030). However, 55% of production companies state that 5G technology deployment is currently not a subject matter for them and mainly state the lack of knowledge on benefits as a reason. Currently, it is missing an approach or model for a use case specific, data-based evaluation of 5G technology influence on the performance of production applications. Therefore, this paper presents a model to evaluate the potential of 5G technology for latency-critical applications in production. First, we derive requirements for the model to fulfill the decision-makers' needs. Second, we analyze existing evaluation approaches regarding their fulfillment of the derived requirements. Third, based on outlined research gaps, we develop a model fulfilling the requirements. Fourth, we give an outlook for further research needs.**

***Index Terms*—5G technology, latency-critical applications, production, evaluation model**

I. Introduction

Latency-critical applications in production, such as motion control, mobile robots, process automation or automated guided vehicles, promise to be essential enablers for performance improvement in production. For these applications, the right communication technology plays a decisive role [1], [2]. The fifth-generation mobile network (5G technology) appears to be an effective way to achieve communication system for latency-critical applications in production. Besides a high bandwidth (up to 20 Gbit/s) and wide coverage (1 million connections per km^2), 5G technology's ability of ultra-reliable low latency communication (URLLC)—targeting an end-to-end latency of 1 ms and a reliability of 99.999 %—is promising for production [3]. This elevates wireless industrial communication to new spheres. Existing use cases, being harmed by cable connection, can be further improved. Additionally, new use cases can be established. The estimated economic impact of 5G technology in production industry is immense. Until 2030, STL Partners expect worldwide production industry gross domestic product (GDP) to increase by up to $740 billion [4].

A survey conducted among over 500 production companies in Germany underlines these 5G-enabled opportunities. 84 % of the companies endorse the predicted productivity increase by 5G technology implementation; 70 % see 5G technology as an essential future technology in production. However, 55 % of the participating companies state that 5G technology deployment is currently not a subject matter for them; more than half of those cite a lack of knowledge on economic benefits as a reason [5]. From these findings, it becomes clear that uncertainty of the actual 5G technology benefits on latency-critical applications in production is inhibiting investments in the technology so far. Currently, it lacks an approach or model for a use case specific, data-based evaluation of 5G technology influence on the performance of production applications.

Therefore, this paper presents a model to evaluate the potential of 5G technology for latency-critical applications in production. First, we derive requirements for the model to fulfill the decision-makers' needs. Second, we analyze existing evaluation approaches regarding the fulfillment of the model requirements. Third, based on outlined research gaps, we develop a model fulfilling the requirements. Fourth, we give an outlook for further research needs.

II. Requirements of Evaluation Model

To meet the outlined demand and enable the evaluation of 5G technology implementation for applications in productions, we derive requirements for the evaluation model, separated in four categories. Section II-A to II-D describe these requirements and justify, why the model must cover these requirements. TABLE I gives an overview of requirements.

A. Scope of Evaluation

Production environment: The term production describes the business activity of generating goods. To generate goods, processes are carried out transforming inputs to outputs. A process transforms physical inputs to process-specific physical outputs. This includes activities that change mechanical and geometric properties of a material (e.g., blanking, drilling, milling, welding) as well as activities for material supply within the production site [6]. As the need for the model originates from production environment, this is one of the requirements.

Single application: Technological production processes can be classified into three main types according to their level of automation: manual, mechanized or automated processes.

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Mechanized and automated processes are partly or fully executed by machines or powered tools, being summarized as "applications". Based on the described needs of industry of having a solid business case, the analysis should be as concrete as possible. The broader the analysis, the more uncertain it is. Analyzing a single application in detail decreases uncertainties and solves the concerns of production companies of a poor understanding of benefits and use cases [7].

Latency-critical application: Latency-critical applications are characterized by a maximum application-perceived latency, which must not be exceeded to ensure application's functionality. If the time between the event and the action is exceeded, failures occur. The maximum application-perceived latency thereby depends on the considered application and its environment. Latency-critical applications promise to be essential enablers for performance improvement in production and require the correct communication technology [8].

B. Consideration of Technology Influence

Wireless communication: Wireless communication has several technical advantages for production systems, e.g., enabling higher flexibility while mitigating cable breakage. Hard to reach locations or remote locations become more easily accessible in wireless communication systems. These technical advantages of wireless communication are expected to result in cost reduction. Therefore, when evaluating the implementation of 5G technology, influence of its property of being wireless should be part of the evaluation [8].

Low-latencies and high reliability: 5G technology's ability of ultra-reliable low-latency communication (URLLC) appears to be major enabler when it comes to improving production, in particular latency-critical applications. Compared to other wireless technologies, expected latencies of 1 millisecond or lower are a unique selling point. The required evaluation model must quantify, whether this ability has an influence on the application's performance [8].

C. Evaluation Approach

Model-based approach: A model is a simplified representation of a certain area of the real world. The model always represents a certain property of the reality. Model-based approaches allow a structured and clear analysis of real processes by making simplifying assumptions and generalizations [9]. As the implementation of 5G technology only affects parts of the application, the model-based approach allows focusing on theses aspects (e.g., networked control systems) and simplifies the other aspects of the application. Quantitative approach: Quantitative methods draw deterministic conclusions from existing data. These are numerical values being calculated with mathematical functions. In contrast to qualitative approaches, no semantic interpretation of the results is necessary. This requirement is central for the model, as qualitative estimations of 5G technology influence in production are existing but must be quantified in a next step [10].

Economic evaluation: Economic evaluation is the process of valuing the inputs and outcomes of two or more alternative activities. This evaluation must be part of the model, as production companies require the knowledge on economic benefits of 5G technology in order to be able to decide for or against the investment in the technology [5].

Technical evaluation: Technical evaluation deals with the production implications of a technology and is measured in terms of industrial key performance indicators (KPI). Besides economic evaluation, KPI are important for the evaluation of a technology, as they can reveal potential for process optimization or new value chains not being expressed by economic evaluation [10].

Ex-ante evaluation: An ex-ante evaluation respectively "prediction" assesses the impact of an object of evaluation (e.g., a technology) before it is implemented for the first time. Simulation studies are used for this purpose, for example. As production companies require a benefit evaluation before investing in 5G technology ex-ante approaches are particularly relevant [11].

Scenario/ Uncertainty analysis: Every prediction is subject to uncertainty. To better interpret calculated results of the model, the model must indicate the uncertainties of its results. This means either to show the uncertainties in the prediction by calculating several possible scenarios, or to include the uncertainties in the result by statistical distribution methods [12].

D. User Orientation & Usability

Production managers (user group): A model must always be user related. In case of this model, the user is the decision-maker in a manufacturing plant. It is the person in charge of the financial and technical evaluation of a modernization of the production line or factory, being able to decide upon the investment of 5G technology.

Individualization of evaluation: When implementing 5G technology, companies might strive for different goals. This depends on the application, the use case or company-wide strategic goals in general. To be suitable for as many uses cases and companies as possible, the model user should be able to individualize the evaluation to only receive the results being interested in. This also decreases the effort during the execution of the evaluation, as it reduces the amount of required data input.

Implementation into software tool: A software automates the calculations of the evaluation. This means that manual execution is no longer necessary. Furthermore, a software tool might reduce or even avoid calculation and execution errors. This facilitates the evaluation process.

III. Existing Evaluation Approaches

Based on defined requirements, we analyze existing research regarding the fulfillment of them. A systematic literature review was conducted using the PRISMA method, as Fig. 1 shows. As 5G technology is still a new field of research, many papers and research being analyzed focuses on wireless communication technologies in general in order to see whether these approaches are transferable to our field of research.

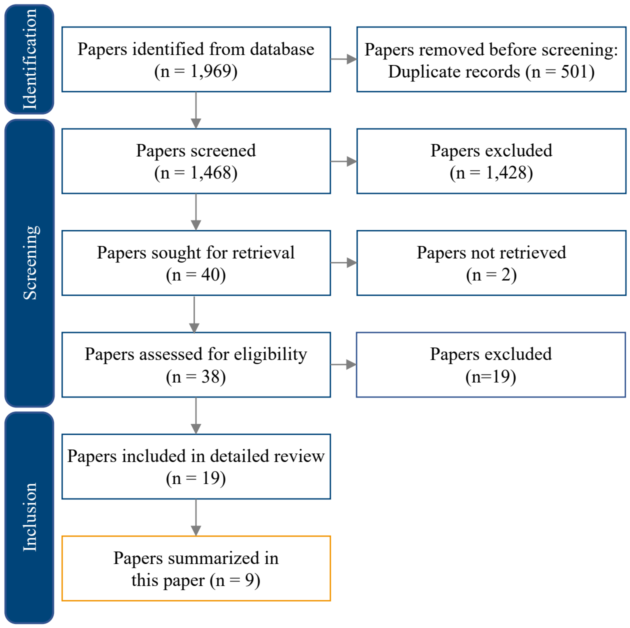

Fig. 1. Overview of analysis of existing evaluation approaches using the PRISMA method

TABLE I
FULFILLMENT OF REQUIREMENTS OF EXISTING RESEARCH

Category	Requirement	Existing Research [13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]
Scope of Evaluation	Production environment	●	●	●	●	●	○	○	○	○
	Single application	●	●	●	○	●	◐	○	○	○
	Latency-critical application	●	●	●	●	○	○	○	○	○
Influence	Wireless communication	●	●	●	●	●	●	●	●	●
	Low latency and high reliability	●	◐	○	●	○	○	●	○	○
Evaluation Approach	Model-based approach	○	●	◐	○	●	●	●	●	●
	Quantitative approach	●	●	●	●	○	●	●	●	●
	Economic evaluation	○	○	○	○	◐	●	●	●	●
	Technical evaluation	●	●	○	○	◐	○	○	○	○
	Ex-Ante Evaluation	○	○	●	○	●	●	●	●	●
	Scenario/ Uncertainty Analysis	○	○	○	●	○	●	●	●	●
User & Usability	User group: production managers	●	●	○	○	○	○	○	○	○
	Software tool	○	○	○	○	○	○	○	●	○
	Individualization of evaluation	○	○	○	○	○	○	○	○	○

The used search engines were Web of Science, Google Scholar and Scopus. The search patterns were combinations of the presented requirements. In total, 1,969 were identified, being published between 2015 and 2021. From these 1,969 papers, the majority (1,428) was excluded as the focus of them lies on improving the communication technology itself, and not the application. 38 papers were assessed in detail, from which nine are summarized in this paper.

TABLE I gives an overview of the results. In the following a short summary of the papers is given, focusing on the gaps they are having regarding the fulfillment of the presented requirements.

Rácz et al. [13] study the performance impact of network delay on closed-loop control for industrial applications. They demonstrate the potential of 5G technology's URLLC ability through an experimental wireless robotic arm control system. The authors observe the need for low-latency communication to achieve the maximum accuracy of the robot at maximum speed. They also show, for which control-loops higher latencies are tolerable. In order to show this, technical KPI (response time and precision of trajectory execution) are introduced and analyzed. However, the economic impact is not considered. Furthermore, the approach is not model-based. The analysis focuses explicitly on the robotic arm, which makes it difficult to transfer to other use cases.

Nakimuli et al. [14] perform several experiments using the 5G-EVE platform to investigate feasible scenarios to deploy a remote-controlled AGV use case using 5G technology and comparing it to 4G technology. The results show that 5G technology not only allows more precise control tasks than 4G technology but also saves energy due to fewer path adaptations. The H2020 EVE platform is thereby based on an information model and thus transferable to other use cases. Nevertheless, the approach lacks an economic evaluation. In addition, both [13] and [14] are experimental studies. There results might be the basis for an ex-ante evaluation model but are not transferred into one yet.

This ex-ante simulation is given by Ashraf et al. [15], who are investigating the technological requirements for 5G technology in the production environment, considering propagation characteristics and simulating latencies and reliability for different encodings of data and frequencies. However, the approach simulates the network capabilities, and not the use cases in terms of technical and economic changes implementing 5G technology.

Lyczkowski et al. [16] analyze the performance of a private LTE network on a factory floor and compare it to WLAN. The focus thereby lies on the influence of network latency, reliability and throughput. In an experimental setup, it is shown that the latency and reliability of LTE is significantly better than that of WLAN. This observation is substantiated with a statistical distribution. However, the approach is solely analyzing the network capabilities based on the production needs, but not drawing statistical conclusions for the production application based on their results.

Stich et al. [17] present a general approach to designing use cases that can be improved using 5G technology. They investigate how successful 5G technology use cases can be developed and marketed for production industry. By systematically analyzing requirements in production and then evaluating and prioritizing these requirements for the various use cases, possible business can be developed with the methodology. Despite the methodology partly includes approaches for technical and economic evaluation of 5G technology in production, the general motivation behind it is different: It is not analyzing, whether current use cases can be improved by 5G technology but designing use cases from scratch. Furthermore, a quantitative evaluation is missing. The influence on latencies on the application is also not part of the model.

Yaghoubi et al. [18] present a model for the evaluation of 5G technology transport networks. The model is intended to help decide which type of network expansion is appropriate, e.g., in an urban environment, which type of access points should be used and whether they should be connected by cable or microwave. The modules cover all important areas of such an investment decision. The existing architecture and topology are considered as well as the market situation, the anticipated broadband demand and the investment and operating costs. It is also analyzed whether an acquisition is worthwhile compared to leasing the corresponding infrastructure. Compared to the research of [13] to [17], the paper has a strong focus on economic analysis. However, the analysis focuses on the cost of the network provider, not the production company as it would be required.

Martin et al. [19] analyze the transition from 4G to 5G, with a techno-economic perspective. By analysis of different technically evolving scenarios, their study defines an annotated roadmap which could provide useful insights about the most suitable use cases for deployments. Moreover, they propose a basic mathematical model which reinforces the feasibility of these use cases by optimizing their deployment costs and perform a sensitivity analysis based on partial derivatives with respect to the main parameters. However, this investigation again focuses on the network operators, not the applications.

Oughton et al. [20] consider a more specific case namely the rollout of 5G in the Netherlands. Here, they explicitly dig into local conditions. The geographical conditions and in particular the population density which is crucial for the achievable data rates per user. In an economic analysis, they looked at the possible re usability of 4G equipment. All these factors are important for network operators, but not for operators of micro cells as in the case of a networked factory.

Nikolikj and Janevski [21] present a conceptual model to assess the business performance of the future advanced wireless and mobile heterogeneous network aiming to preserve enormous broadband demand in the future. In a detailed analysis strategies are developed for network operators to cope with the immense data volumes of the twenties. The authors assume up to 25,000 Gbit/s/km^2 for the so-called virtual reality office. A detailed analysis is carried out to determine which wireless technology should be used in which areas and whether all technology can be used in the future. The focus is on economic profitability and meeting user requirements. Overall, the analysis is very detailed. However, such an assessment for network operators cannot be transferred to the production environment without further ado, since, as described in the requirements, production-related aspects should also be taken into account in order to properly assess the potential of 5G in production.

As TABLE I summarizes, current research does not fulfill the evaluation model requirements. There is a lack of economic analyses in the production area and of approaches for the inclusion of production-related parameters and the potential in new value chains made possible by 5G. Nevertheless, the detailed economic analyses from the network operators can be helpful in an economic evaluation of the investment costs.

IV. Development of Evaluation Model

Based on the requirements and existing approaches, we develop an evaluation model for 5G technology implementation for latency-critical applications in production. Fig. 2 shows the general structure of the evaluation model, which is implemented in web2py. Section IV-A to IV-E describe the model components.

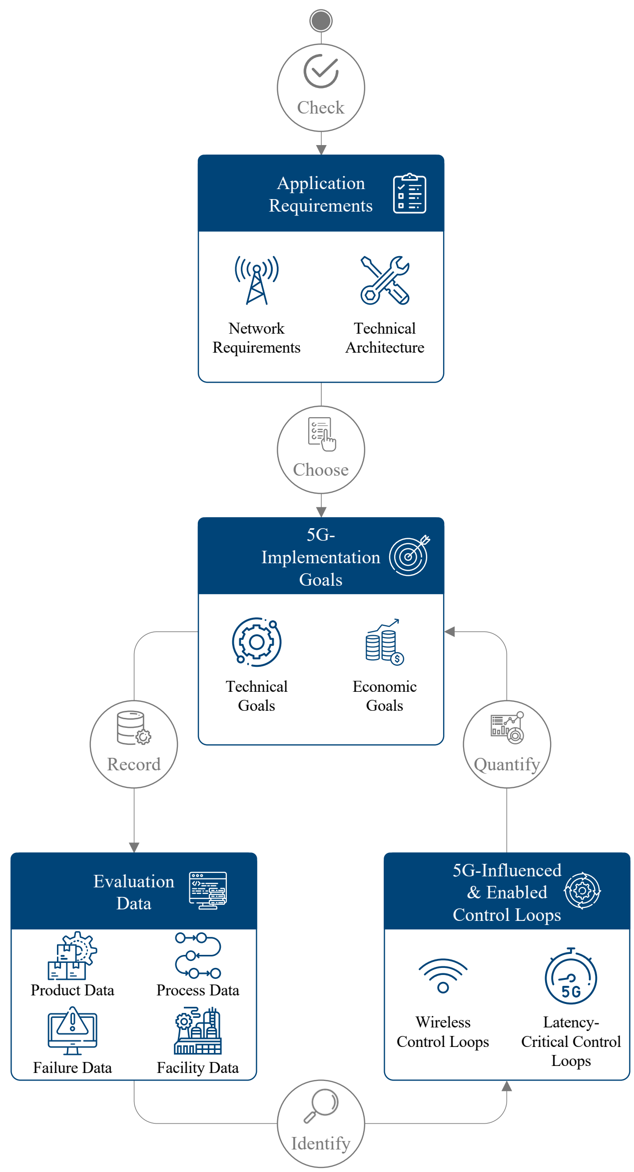

Fig. 2. Structure of the model for evaluating the potential of 5G technology for latency-critical applications in production

A. Application Requirements

To conduct a detailed, but efficient evaluation, a first check whether the application fulfills the requirements to be further analyzed is done. On the one hand, network requirements of the application are checked, e.g., required latency, reliability and communication range. After entering the requirements from an application point of view, the model checks, whether any other communication network (e.g., 4G, ZigBee, WiFi) would be suitable.

As some applications do not require 5G technology, this first check might save time for the model user. This check list is based on the overview of Kiesel et al. [8]. Besides the check of network requirements, technical architecture of the application is checked. This includes, e.g., sensors, actuators, data network, control units. If technical architecture requirements are not fulfilled, the evaluation can be executed, however, user should be aware of the fact that 5G technology implementation might be expensive.

B. 5G-Implementation Goals

After the first application check, the model user can individually choose the goals he or she aims for when implementing 5G technology. Thereby, the model distinguishes between technical and economic goals. According to [10], seven distinctive goals were determined based on prospected benefits by implementing wireless communication technologies, especially 5G technology, in production. These goals are operationalized by KPI to be measurable. The goal "quality", as an example, is operationalized by the KPIs "first pass yield", "quality ratio", "rework ratio" and "scrap ratio". These KPI are assigned to the trends maximizing (max) or minimizing (min). Max means, that the KPI has to be increased to improve the goal (e.g., higher quality ratio = higher quality). Min on the other hand means, that a decreased KPI improves the goal (e.g., lower scrap ratio = higher quality). This trend is relevant, once the change of KPI after 5G technology implementation is traced back to the goal. As all goals have a positive trend, the max-KPI are added with a positive sign, the min-KPI with a negative sign. This was executed for every goal. To quantify economic benefits, user can choose between the economic evaluation methods Net Present Value and Return on Investment, so either choose one, both or none of them.

C. Product & Process Data

Based on the chosen goals, the model automatically shows the user, which data needs to be entered to evaluate the application. Thereby, data is distinguished into four categories, which are product data, process data, failure data and facility data in order to facilitate the data entry for the model user. By connecting the evaluation data with the chosen goals, user does not enter "unnecessary" data but only relevant data.

D. 5G-Influenced & Enabled Control Loops

The benefit of 5G technology for latency-critical applications mainly emerges by allowing networked control systems [8]. Thereby, two effects main effects of 5G technology are analyzed in the model. On the one hand, the effect of being a wireless technology is analyzed. This enables completely new applications (e.g., drones), which can be analyzed with the model. On the other hand, the better reaction times due to low latencies have an impact on the application and must be measured.

E. Quantification of 5G-Implementation Goals

To finally quantify the impact on 5G technology implementation on latency-critical applications in production, the loop between the modules "goals", "data" and "5G-influenced control loops" is closed. First, the delta on basis of the recorded data (e.g., produced quantity before and after 5G implementation) through the described advantages in IV.D is calculated. This has an influence on the KPI, being expressed in percentages. Due to the defined relations between KPI and goals, this change can be tracked back to the goals. Thereby, each KPI has the same weight and influence on the goal. This way, the model enables to quantify the influence of 5G technology for latency-critical applications in production. The evaluation only considers the benefits of the end-user. It does not consider the network cost. After using the model, production company should be aware of the value it would be willing to invest into 5G technology.

V. Conclusion

This paper develops a model to evaluate and quantify the benefits of 5G technology for latency-critical applications in production. Thereby, a model consisting of four sub-modules is presented. The model closes the presented research need and especially enables a data-based quantification of the influence of 5G technology implementation for latency-critical applications.

However, sub-modules of the model still have to be further developed, especially the module "5G-Influenced & Enabled Control Loops". Furthermore, the web2py-based model needs to be further improved. Finally, the validation of the model on a real use case has not been done yet and is part of current research within the project 5G-SMART.

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