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An advisory system to support Industry 4.0 readiness improvement

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Abstract

Industry 4.0 requires companies to go through a complex transformation. Numerous maturity models offer to measure the readiness of an enterprise for the transition to a new operation mode. However, there is a lack of research efforts in developing an advisory tool for digital readiness improvement recommendations. This study aims to create a systematic approach for building an advisory decision support system based on Industry 4.0 Maturity Models. The development of the proposed system has gone through three stages, including analysis of the existing maturity models, reviewing the development methods of decision-support systems, and industrial interactions with manufacturing companies via the project online recommendation tool. The developed advisory system provides I4.0 readiness recommendations based on industry best practices, integration of recommendation databases with a maturity model, information filtration algorithm, and weight-based prioritisation of suggestions. Moreover, an interactive and user-friendly interface was developed to enable the user to utilise the system easily and efficiently.

Keywords: Industry 4.0; Expert system; Maturity models; Advisory system; COMMA 4.0.

1. Introduction

The production industries are undergoing a global transformation known as Industry 4.0 (I4.0), driven by the explosion of new digital technologies such as cloud computing, the Internet of Things, Big data, and other digital opportunities [1]. The initiatives to take advantage of new opportunities often involve transformations of main business processes that affect company in different areas [2]. However, manufacturing practitioners frequently underestimate the problem of misunderstanding the I4.0. Some significant barriers might be faced by companies while attempting to develop systematic roadmaps due to the lack of understanding of main I4.0 concepts, relevant methodologies, effective processes, and other aspects on their way to transit into I4.0 [3]. In order to help companies, research groups from universities, government institutions, and consulting companies, this paper has introduced a decent range of I4.0 assessment tools/maturity models in recent years. The main aim of those tools is to help companies measure their readiness to I4.0 [4]. A set of recommendations can also be part of the maturity model provided to the companies as an outcome of the maturity assessment. However, as was found out from the literature review, almost half of the investigated models fail to provide recommendations toward a successful digital transformation. In contrast, those that provide recommendations are revealed to be either general, which means it doesn't depend on the specific parameters of the company and some recommendations can be irrelevant. The others require human expertise, which means expensive consultation and time taking. Therefore, it can be concluded that there is a need for a system that can automatically calculate the company's maturity level, generate the recommendations report based on the score, making it score-sensitive so only relevant recommendations will be given. Additionally, it is critical that system provide it all at once as soon as the survey is completed, saving the time for users without extra expenses and time [5]. Therefore, this study aims to develop a rule-based advisory system serving as a comprehensive instrument to assist companies with the

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I4.0 transformation. The proposed tool generates a company-specific roadmap based on the COMMA 4.0 (Comprehensive I4.0 Maturity Assessment Model) structure [6] and can be an extension of many well-established I4.0 maturity models. This paper first overviews the existing readiness assessment models for whether they offer a recommendation system and, if so, explores the scope of the system. Afterwards, it presents the advisory system components developed based on the Design Science Approach (DSA) [7] with a real-life use example.

2. Literature review

The era of digitization and automation is characterized by trends such as self-optimization of the industries in all parts of the supply chain processes [8]. These changes demand a comprehensive approach to achieve the best results. From both strategy and technology perspectives, the transit to I4.0 requires a step-by-step roadmap towards the state of full maturity of an enterprise [9]. In the context of I4.0, the maturity model is a concept that assists companies in measuring readiness and provides the relevant solutions (in some cases) for competitively facing the fast and changing environment of I4.0 [10]. The maturity aspect/sub-dimension is the smallest constituent element of the maturity model, responsible for a particular aspect of development criteria, assessing the degree of readiness for a company's transformation. Several sub-dimensions upon their assessing measures can be grouped to the main dimensions. Maturity level is a degree/score of readiness calculated based on maturity aspects [11]. Recommendations can enrich the model and support the companies in their way to the evolution.

Table 1. Reviewed Maturity Models

Recommendation type	Maturity Models
No recommendations	• A Maturity Model for Manufacturing 4.0 in Emerging Countries [12], • DREAMY - Digital Readiness Assessment Maturity Model [13], • I4.0 Maturity Assessment Framework [14], • I4.0 Maturity Model [15], • I4.0 Maturity Model [16], • I4.0-Maturity Model [17], • InAsPro Maturity Model [18], • ManuTech Maturity Model [19], • Maturity and Readiness Model for I4.0 Strategy [20], • Reference Architecture Model Industrie 4.0 (RAMI4.0) [21], • SIMMI 4.0 – System Integration Maturity Model I4.0 [22], • The new I4.0 Maturity Model for MT companies [23]
General recommendations regardless of the actual maturity level	• A Categorical Framework of Manufacturing for I4.0 and Beyond [24], • I4.0 Maturity Model [25], • Maturity Model for Data-Driven Manufacturing (M2DDM) [26], • Three-Stage Maturity Model [27]
Specific recommendations – human expertise	• 360DMA [28] • Acatech Industrie 4.0 Maturity Index [29] • SIRI - Smart Industry Readiness Index [3], • The Connected Enterprise Maturity Model [30] • Digital Operations Self-Assessment [31]
Specific recommendations – Automated expertise	• IMPULS—Industrie 4.0 Readiness [32] • WMG Model [33]

Based on the systematic literature review approach (SLR) [34], 23 selected I4.0 maturity models were studied in detail and allocated by the recommendation types. The SLR research question was: "Do the existing I4.0 maturity models offer suggestions for readiness improvement based on the assessment results?". Despite the variety of existing maturity models, it was identified that only a few of them provide recommendations to improve the maturity level (Table 1).

According to the collected data, the following results have been derived:

- 14 Maturity models out of 23 do not provide the information in open-access or reveal the complete model;
- Only 11 out of 23 studied maturity models offer recommendations to the companies;
- Out of those 11 maturity models, four provide general recommendations regardless of the actual maturity level;
- Another five maturity models give specific recommendations only upon the involvement of the external consultant;
- The rest two maturity models include an advisory system to generate recommendations to the user companies.

According to the derived results, it is evident that maturity models with limited information in the articles or unavailable for extensive application can be eliminated from the sample. Four maturity models provide only general recommendations regardless of the actual maturity level. Such recommendations have low value due to the lack of connection between the actual situation and the targeted level that the company aims to achieve [35]. On the other hand, five investigated maturity models that provide specific recommendations require offline interviews and on-site consultation, which can be a time and resource-consuming process for the companies [28]. The last two models do not require an external consultant and provide specific recommendations using an advisory system. However, the recommendations are given only based on the general score of the main dimension, ignoring the results of sub-dimensions within it. This can make the recommendations inaccurate and may not reflect the actual situation objectively. As a result, the development of tailored roadmaps and/or contextualised recommendations that are attached to the maturity model is required [35]. The contextual approach of the maturity model application requires the ability to adapt to "company-specific situational characteristics", as there might be varieties of maturation paths under different contexts. It remains a crucial issue for putting the maturity models into operation [28]. In order to fill this gap, this study offers an automated advisory system covering all essential characteristics of Industry 4.0. It can generate company-specific recommendations thanks to the rule-based decision engine able to utilize the company data acquired through the maturity model. The automated advisory system has been developed as an important component of the Comma 4.0 developed to assess the I4.0 readiness of enterprises in developing economies [6]. Moreover, the system can be adapted to numerous other maturity models that have a similar structure to that of COMMA 4.0 since the knowledge base and algorithm rules are standardized.

3. Method

The design science approach (DSA) was adapted for this study to develop the rule-based advisory system [7]. First, an architecture of the advisory system was designed following the principles suggested by [36]. According to [36], the advisory system should be extendable, simple, and explicit. To achieve this, the system's output depends on uniform rules: "IF in aspect X, the score is Y, THEN the recommendation is Z". Homogeneity of rules enabled easy modification and intuitive visualisation using spreadsheets. As well, the advisory systems use the pre-prepared *knowledge base* to support humans in the decision-making process. The systems are constructed in a way, where the human/experts' knowledge is collected and embedded in the software, so the system will be able to generate solutions [37].

Therefore, secondly, the authors conducted a systematic literature review to fill the knowledge/recommendation base [38]. Keywords were "Industry 4.0", "digitalization", "smart factory", "transformation", "maturity", "readiness", "model", "assessment", "roadmap", "decision support system", "advisory system", "expert system". In total, 370 documents were retrieved from Google Scholar and Scopus databases. Next, duplicates, irrelevant and not-peer-reviewed papers were excluded. The rest 165 journal and conference papers were subjected to full-paper qualitative content analysis [39]. Overall, the information retrieved from 72 reviewed papers was used to generate 128 recommendations for all combinations of maturity scores and levels.

Next, in order to complement the knowledge base, the opinion of the experts' panel was included. The experts' panel consisted of five professors with a Ph.D. degree in engineering and management fields and representatives of management consulting companies with 10+ years of experience.

Furthermore, all experts were invited to discuss the drafted knowledge base. Recommendations were reformulated, clarified, split, merged, and detailed until all expert panel members fully agreed.

In the next step, the advisory system was implemented and automated as software with a user interface. Finally, the advisory system was launched online and validated by application in 96 Kazakhstan companies, 35 of which shared their expanded feedback on improvement. Additionally, five companies provided their feedback by thinking aloud immediately after receiving the report and reviewing the suggestions [40].

4. Results

The proposed advisory system adapted and modified the commonly practiced architecture of expert systems [36,37] and consists of five components: interface, database, knowledge base, decision engine, and explanation sub-system (Fig. 1). The overall process of the advisory system can be presented as follows:

- The first component, the interface, has a twofold purpose. First, it serves as a user-friendly data input shell. Secondly, it outputs valuable conclusions to users. For this advisory system, the data input interface is taken from the developed COMMA 4.0. Company managers need to fill the COMMA 4.0;
- After receiving responses, the system of COMMA 4.0 automatically calculates the maturity score considering aspects weight calculated using Analytical Hierarchy Process method (AHP) [41];
- Next, a rule-based decision algorithm selects appropriate recommendations from the knowledge base based on the received score/level by the company for each subdimension;
- Finally, the I4.0 readiness improvement roadmap is generated, with the critical recommendations being highlighted and ranked by priority (Fig.1).

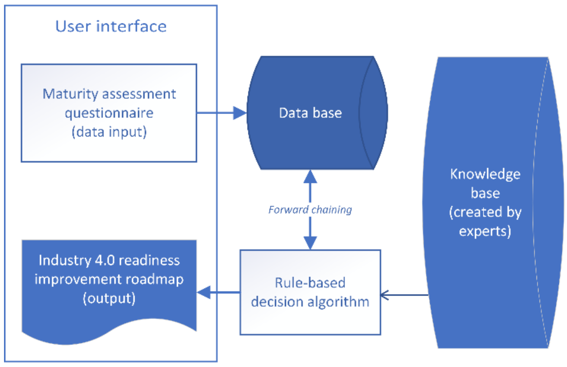

Fig. 1. Structure of the proposed advisory system

4.1. Interface: COMMA 4.0

COMMA 4.0 consists of 32 sub-dimensions grouped into five main dimensions. An overview of the maturity dimensions and their connected measures is provided in Table 2. Each sub-dimension is presented as a matrix-format question with five answer options, each having a unique description (Fig. 2). The selected option indicates the sub-dimension score and is stored in a database. COMMA4.0 has five discrete maturity levels: level 1 – "Entrant", level 2 – "Beginner", level 3 – "Learner", level 4 – "Integrator", and level 5 – "Expert". These levels are defined by the weighted mean of scores of all relevant sub-dimensions.

Fig. 2. Data input through the interface of COMMA4.0

The output interface provides companies with the I4.0 maturity improvement roadmap consisting of relevant recommendations and indicating company strengths and ranked weaknesses. Moreover, all the results are visualised by relevant diagrams and radar charts.

Importantly, a dictionary with the descriptions of the I4.0 terms is provided for all users since many of those concepts are novel, technical and have indeterminate scope. This improves clarity and coherence of understanding among researchers, experts, and a company, thus enhancing the efficiency of the advisory system. Moreover, it is implemented as a survey tooltip that displays the information if hovered over (Fig. 2).

Table 2. Maturity dimensions and aspects of COMMA4.0

Maturity Dimension	Maturity Aspects (sub-dimensions)
Strategy and Organisation	Strategy implementation; business performance management; business performance indicators; state of ICT function; ICT systems budget management; leadership support for I4.0; innovation management system; collaboration with stakeholders for 4.0.
Workforce Development	Digital competency; support for employees' development; change acceptance level.
Smart Factory	Automation of production system; equipment upgradability; M2M communication (data exchange) level; supply chain communication/integration; digitization of enterprise data; observability of production; ICT Architecture; cloud services utilisation.
'Smart Processes	Standardisation and improvement of BPs; use of automation and business information systems (MIS/ERP); data-driven decision-making; maintenance approach; quality management systems
Smart Products and Services	Intellectual property development; digital products; digital services; product customisation degree; frequency of product/service upgrades; customer data utilisation; sales channels used; revenue from data-driven services; plans for digital features.

4.2. Database

Database stores the information about the current maturity status of a company. COMMA 4.0 captures relevant information pieces through the input interface. The database has a simple data structure of key-value pairs. Keys are 32 subdimensions, while values are company scores in *those aspects.* The score indicates the discrete readiness level ranging from 1 to 5 inclusively.

4.3. Knowledge base

The knowledge base is a set of recommendations rules developed by authors and experts' panel, as was mentioned in the Method section. These recommendations suggest changes in the company's organization, human resources, technologies, assistance systems, transparency, and data management [42].

Each of 32 aspects has four recommendations for four maturity transition steps (level 1 → level 2; 2 → 3; 3 → 4; 4 → 5). An example of recommendations is presented in the Application case part (Table 4). Each recommendation is a semantically complete guide to improve sub-dimension by one level in this structure. In total, 128 unique recommendations were produced. For maturity aspects with level 5, detailed guidelines are not provided.

4.4. Decision engine

The decision engine performs inference procedures and applies rules to create a roadmap out of database and knowledge base. A rule-based decision algorithm was implemented and automated using JavaScript. The roadmap is created by sequential application of the following rule to all maturity aspects: "IF in aspect X, the score is Y, THEN the recommendation is Z". For each sub-dimension, a recommendation is retrieved from the knowledge base. The content of the suggestion is determined by the current sub-dimension score. Afterwards, these guidelines are combined and added to the report.

According to the Theory of Constraints, a company should focus on the most critical issues to attain maximum efficiency [43]. This focusing can be achieved by identification of the company bottlenecks. In the proposed advisory system, company bottlenecks are the maturity aspects with scores $r_i \leq \bar{x} - 0.67s$. Under this notation, r is the response to i-th question (sub-dimension), while $\bar{x}$ and s are the mean and standard deviation of all responses of the studied company [44]. These values are calculated using Formula 1, where N is the total number of relevant sub-dimensions for the company.

On average, this rule selects 25% of aspects as bottlenecks that constrain the company's transformation. Furthermore, the list of bottlenecks is sorted by priority from highest to lowest based on sub-dimensions' global weights measured by AHP. COMMA 4.0 provided these weights. Similarly, all maturity aspects with scores $r_i \geq \bar{x} + 0.67s$ are marked as company strengths. This sub-system suggests taking advantage of existing drivers.

$$\bar{x} = \frac{\sum_{i=1}^{N} r_i}{N} \qquad s = \sqrt{\frac{\sum_{i=1}^{N} (r_i - \bar{x})^2}{N-1}} \tag{1}$$

4.5. Explanation sub-system

The explanation is a justification of the selected recommendations to users. Since recommendations are based on the data collected from users, information about current company scores is embedded into recommendations.

5. Application case

One of the companies that used the proposed system is a local tracked vehicles manufacturer with 150 employees. A middle manager of this company filled out the online maturity assessment questionnaire in 15 minutes. This section illustrates the decision algorithm's logic while generating a roadmap for the Smart Processes dimension (Fig. 3).

None of the maturity aspects in Smart Processes received a score of 5. Hence, all sub-dimensions received related recommendations. These are presented in Table 3.

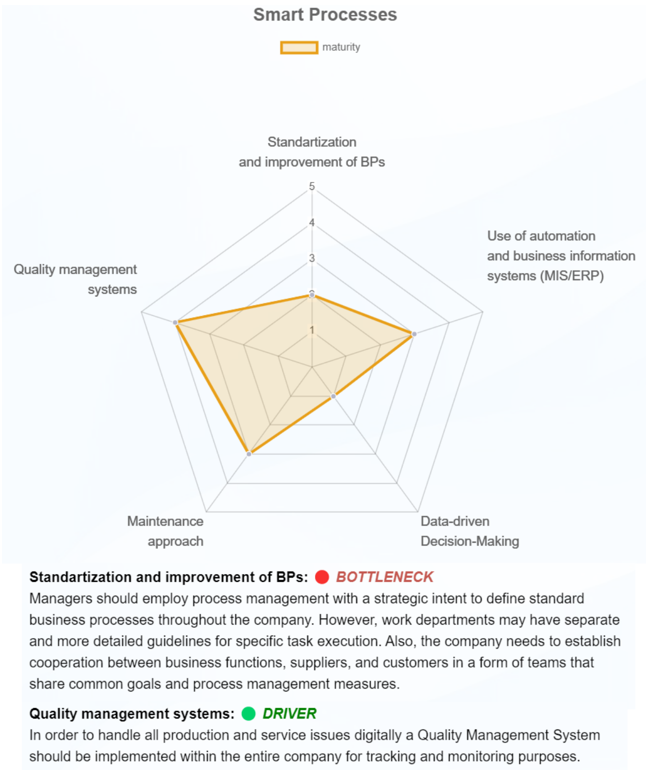

Fig 3. Part of the analysis report displayed to the respondent in the case study

For this company, considering all scores in all sub-dimensions, $\bar{x}$ is 2.60 and s is 0.79. Since bottlenecks are aspects with scores $r_i \leq \bar{x} - 0.67s$, business process standardization (score=2) and data-driven decision-making (score=1) are marked as company weaknesses. The first of these bottlenecks has a priority, according to AHP analysis. Likewise, since drivers are aspects with scores $r_i \geq \bar{x} + 0.67s$, quality management (score=4) is marked as company strength.

Table 3. Recommendations provided to the selected company

Sub-dimension and transition	Recommendation
Standardisation of business processes (2 → 3)	The company should implement process management with a specific aim of standardising processes across the company. At the same time, departments may have more flexible and detailed instructions for project execution. Moreover, integration of business branches, supply chain, and clients should be achieved by creating special teams. ...
Process digitization (2 → 3)	Complex IT systems are required to shift to the complete digitization stage. Moreover, the company can automate standard processes with powerful tools such as ERP. ...
Data-driven decision making (1 → 2)	Historical data is essential in all processes of a company. Historical data should be used for lower-level decision-making purposes, for example, in sub-processes and work packages. ...
Data-driven maintenance (3 → 4)	The company should conduct predictive maintenance using near-real-time historical data to handle emergencies in advance. This way company will have tools that enable the prediction of future failures. ...
Quality control (2 → 3)	To handle all production and service issues digitally, a Quality Management System should be implemented within the entire company for tracking and monitoring purposes. ...

The provided recommendations can be used in several ways such as:

- Analyzing the current state of the company, based on results of COMMA 4.0, where the strong and weak points are represented;
- Prioritization of the improvement plans based on the importance and performance of the selected sub-dimension;
- Tracking and controlling the improvement process using the COMMA 4.0 and advisory system

6. Conclusion

This paper presented a rule-based advisory system for Industry 4.0 (I4.0) maturity improvement. The proposed advisory system captured the expert knowledge, converted it to recommendations and embedded it into the COMMA 4.0 maturity model.

The value of the proposed automated advisory system for companies is in the provision of expert knowledge and information filtering. The system is able to assess company readiness and provide recommendations relevant to the combination of factors unique to that company. In total, high score sensitivity allows to manage up to $8{\times}10^{24}$ combinations of factors. The output of the system is the comprehensive roadmap covering the broad scope of I4.0 aspects, suggesting readiness improvement actions and indicating company weaknesses. Moreover, the presented advisory system has low cost and can provide the results immediately after the survey is completed. Furthermore, the developed advisory system can be reused and does not require an expert external operator.

This study contributes to academic research by demonstrating the applicability of a proposed framework for creating advisory systems for I4.0 maturity improvement. Moreover, the framework covers knowledge acquisition procedures involving questionnaires, SLR, and discussion.

Due to the nature of interview-based research, the preference bias of experts is among the critical limitations of this study. Such fallacies could have led to over-emphasis of some suggestions and neglection of other factors. Moreover, the relevance of suggestions might degrade if the survey respondent has low awareness regarding the company affairs. However, the latter concern can be negated by combining the data from skilled employees of various departments.

Further research is needed to extend the I4.0 knowledge base by providing a detailed list of activities that can contribute to I4.0 maturity improvement. Moreover, the sensitivity of the advisory system can be further improved by introducing new rules that consider company context parameters, such as operation domain, employee number, revenue, and country. These improvements would improve the accuracy of suggested action plans and their applicability.

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