ADAPTIVE 2025

The Seventeenth International Conference on Adaptive and Self-Adaptive Systems and Applications

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ADAPTIVE 2025 Editors

Mark J. Balas, Mechanical Engineering Department, Texas A&M University, USA

ADAPTIVE 2025

Forward

The Seventeenth International Conference on Adaptive and Self-Adaptive Systems and Applications (ADAPTIVE 2025), held on April 6 – 10, 2025, continued a series of events targeting advanced system and application design paradigms driven by adaptiveness and self-adaptiveness. With the current tendencies in developing and deploying complex systems, and under the continuous changes of system and application requirements, adaptation is a key feature. Speed and scalability of changes require self-adaptation for special cases. How to build systems to be easily adaptive and self-adaptive, what constraints and what mechanisms must be used, and how to evaluate a stable state in such systems are challenging duties. Context-aware and user-aware are major situations where environment and user feedback is considered for further adaptation.

The conference had the following tracks:

- Self-adaptation
- Adaptive applications
- Adaptivity in robot systems
- Fundamentals and design of adaptive systems
- Computational Trust for Self-Adaptive Systems
- Assurances and metrics for adaptive and self-adaptive systems

Similar to the previous edition, this event attracted excellent contributions and active participation from all over the world. We were very pleased to receive top quality contributions.

We take here the opportunity to warmly thank all the members of the ADAPTIVE 2025 technical program committee, as well as the numerous reviewers. The creation of a high quality conference program would not have been possible without their involvement. We also kindly thank all the authors that dedicated much of their time and effort to contribute to ADAPTIVE 2025. We truly believe that, thanks to all these efforts, the final conference program consisted of top quality contributions.

Also, this event could not have been a reality without the support of many individuals, organizations and sponsors. We also gratefully thank the members of the ADAPTIVE 2025 organizing committee for their help in handling the logistics and for their work that made this professional meeting a success.

We hope ADAPTIVE 2025 was a successful international forum for the exchange of ideas and results between academia and industry and to promote further progress in the area of adaptive and self-adaptive systems and applications. We also hope that Valencia provided a pleasant environment during the conference and everyone saved some time to enjoy this beautiful city

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Table of Contents

A Comparative Overview of Success Factors for Sustainable and Digital Business Models

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***Abstract*— Digitalization and Sustainability are two global megatrends, that lead to a changing world. Companies are therefore adapting their business models towards these transformation necessities. To adapt successfully to these alterations, it is important to know the success factors of both the business model types. However, there is a lack of a comparative overview of both the success factors for the included business model types, such as sustainable and digital. A literature review was conducted to investigate the similarities between these two types. As a result, success factors of digital and sustainable business models have been identified through the literature review, including factors that are mentioned for both business model types and factors that are found exclusively for one type of business model. The factors can be tested and evaluated afterward in living labs. Knowledge about these factors can support entrepreneurs in the development or innovation process of their sustainable and digital business models. This paper deals with adaption, for example, what success factors are found for companies to adapt their business models. Here, topics from the Adaptive Conference are addressed, such as adaptive economic applications.**

Keywords-business model; digital business model; sustainable business model; success factors; business model innovation.

I. INTRODUCTION

A. Motivation and Research Problem

The world is changing! The consequences of those changes are already visible. For example, it can be assumed with a high degree of probability that strong temperature anomalies are linked to global warming [1]. Megatrends are developments on a worldwide scale that persist for several decades and also lead to a changing world [2]. Digitalization and Sustainability are two of these global megatrends [3] [4].

Companies are already partially adapting their business models towards these transformation needs. For example, business models are adapted to new opportunities of offline and online IT, while there is also an adaption pressure because of challenging sustainability topics [5] [6]. To achieve a targeted and low-risk business model adoption, it is important to know the exclusive and common success factors of sustainable business models and digital business models.

Several factors can be found in the literature for exclusively mentioned digital business models or e-business models. For example, existing work that deals with the key success factors with a focus on platform-driven models [7]. In addition, criteria of success were identified for e-marketplace models in the B2B domain [8].

In addition, there are already several success factors in the literature for exclusive mention of sustainable or circular business models. For instance, existing work is about the criteria for the success of circulating business models [9]. Furthermore, it is possible to find results in the domain of creating sustainable digital business models and conventional business models, which focus on the tensions in model creation [10]. However, there is no comparative review showing the success factors for both business model types spanning several domains. This work addresses this research gap.

If overlapping success factors for digital and sustainable business models and factors, that are exclusively mentioned for one business model type, can be identified, entrepreneurs of the business models are able to adapt and further develop or implement their business models under consideration of those factors.

The aim of this paper is therefore to present a comparative overview of the success factors of both, sustainable and digital business models.

In the scope of the paper, the following research questions are addressed:

RQ 1. Which success factors of digital and/or sustainable business models can be identified?
RQ 2. Which success factors of question 1 are mentioned exclusively to one type of business model?
RQ 3. Which of the success factors defined in question 1 apply to both business model types, the sustainable and digital ones?

B. State-of-the-Art and Definitions

To compare digital and sustainable business models it is necessary to mention scientific work that already combines the two business model types.

For instance, there is already research in the direction of digital and sustainable business models that addresses the question of how sustainability can be merged with the digital business model [11]. The work describes that digital technologies not only focus on more efficient production processes but also that sustainability can even be a central element of digital business models [11]. For this kind of digital and sustainable business model, several archetypes can be identified [11].

Another example that combines digital and sustainable business models deals with the success factors for start-ups in the business-to-business domain [10]. Thereby internal factors like how the technologies are used or external factors like funding can be mentioned [10].

Besides the research in the direction of both business model types, there is also research that addresses only one of the mentioned business model types. An example deals with the sustainable business model type and the identification and ordering of those models [12]. Thereby several categories for the usage of this business model type, like “energy” or “fashion”, can be mentioned [12].

Furthermore, there is research in the field of digital business models. For instance, one example deals with the conceptualization of research fields of digital business models, concept ordering, and categorization [13]. There is already research that addresses both business model types and research in the field of only one business model type. However, there is no comparative overview that focuses on the success factors for several application domains.

Before the method is described, explanations or definitions of the relevant terms like “business model”, “success factors”, “digital business model” and “sustainable business models” that are used in this work are important to clarify. Having a look at the business model literature, it should be mentioned that there are several definitions of this term. These different definitions can also be classified into different types, like a type for patterns of organizational parts, a type for more abstract schemes, and a type for specific smaller parts [14]. In addition, definitions of sustainable and digital business models can be found. One definition describes for example *“sustainable business models as a simplified representation of the elements, the interrelation between these elements, and the interactions with its stakeholders that an organizational unit uses to create, deliver, capture, and exchange sustainable value for, and in collaboration with, a broad range of stakeholders*” [15]. This review is based on this definition because it includes the already mentioned important sustainability topic and is a wide description to receive a broad topic overview in this review. Due to the close similarities business models that are described in the sustainable context, like circular business models and agriculture business models are also covered by this definition in this review.

To give one suggestion for the digital business model one definition is “*Enhanced resource optimization, characterized by intangibility, businesses’ uniqueness, and core values, centering around experience, platform, and content*” [16]. To receive a wide scope of the literature a description that focuses less on resource optimization was chosen: “*A business model is digital if changes in digital technologies trigger fundamental changes in the way business is carried out and revenues are generated.*”[17]. Due to the close similarities business models that are described in the digital context, like AI technology-based, e-business, and digital platform-based business models are also covered by this definition in this review.

There are also several “success factor” definitions. To give one example, that was also used in the scope of this article, due to its broad thematic range: “success factors” are for instance “the limited number of areas in which results, if they are satisfactory, will ensure successful competitive performance for the organization” [18].

C. Structure

This work is structured as follows: In Section I, this work is introduced, including the Motivation, Problem Relevance, and State of the Art. Section II deals with the methodology used. In Section III the results of this literature review are described. Section IV deals with the conclusion and the discussion.

II. METHODOLOGY

The conducted literature review was based on the “Guidelines for Performing Systematic Literature Reviews in Software Engineering”[19] because it is suitable with small adjustments for the domain of business models, especially digital business models. The whole methodology is explained in this section. These guidelines were already used several times in scientific papers [20][21]. The mentioned work focuses on extensive guidelines for researchers in the software engineering domain [19]. With the help of these guidelines, success factors were identified. Subsequently, we identified the overlapping factors for the two types of business models. For this literature review, a PRISMA checklist was created in addition, in order to make sure that the review included important topics, like the used criteria [22].

The main aim of this literature review is to create a general overview of the success factors for sustainable and digital business models focused on several application domains. The literature review was conducted in four steps, which are shown in Figure 1 as dark blue boxes. The first step is finding suitable literature with specific search entries.

Figure 1. Steps Literature Review

This was followed by the source selection in a way that sources were selected, that were connected to the research questions. The output of the source selection was used as

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input for the sorting process. Afterward, the evaluation process for the sorted success factors was conducted.

A. Search for Scientific Sources

The goal of the first step was to find scientific publications in the mentioned area. In order to find the references, different search input was used, which is shown in Table 1, including the keywords, the search entries, and the access dates. Searches were conducted on four comprehensive search engines to get a broad range of literature: Google Scholar, MDPI Search Platform, Science Direct, IEEE and JSTOR [23][24]. To receive a broad literature span it was searched for any type of publications. The search entries were accessed between 29/08/2024 and 04/03/2025. The keywords were formulated in the English Language to cover a broad range of potential publications. Circular (economy) business models were also included because they can be found several times in the literature and are also cited as examples of sustainable business models [12].

TABLE I. SEARCH INPUT

Keywords:

- digital business model success factors
- success factors circular economy business models
- sustainable business model success factors
- e-business model success factors

Platform:	Entries:	Access Dates:
Google Scholar	Any Time, Sort by relevance, Any type, for each keyword	29.08.2024 - 13.09.2024
Platform:	**Entries:**	**Access Dates:**
MDPI Search Platform	1996-2024, Sort by relevance, Any type, for each keyword	29.08.2024 - 13.09.2024
Platform:	**Entries:**	**Access Dates:**
Science Direct	Any Time, Sort by relevance, Any type, for each keyword	29.08.2024 - 13.09.2024
Platform:	**Entries:**	**Access Dates:**
JSTOR	Any Time, Sort by relevance, Any type, for 2 keywords	29.08.2024 - 13.09.2024
Platform:	**Entries:**	**Access Dates:**
IEEE	1996-2024, Sort by relevance, Any type, for 2 keywords	02.02.2025- 04.03.2025

Due to the similarity of the findings, we searched for success factors, success components; success indicators; and competitive advantage factors. Furthermore, due to similarities e-Business, electronic business, AI-based, and platform-based business models are included. To get a broad literature span, more than 100 publications were selected: The 10 most relevant for each keyword of the search engines Google Scholar, MDPI Search Platform, Science Direct, and the 10 most relevant for 2 keywords of the platform JSTOR and IEEE. The result of the search process was more than 100 publications, 160 in total. The complete list of the 160 publications is available but would exceed the number of pages of this article.

B. Source Selection

After the collection of the 160 publications, the filtering process started according to specific criteria. Thereby the publications were excluded, that did not fulfill the following criteria (Here the authors have decided):

- *Addresses one of the three research questions (after reading the title and abstract)*
- *English language;*
- *Common format: Like pdf-format*
- *Publications: Books or papers (article type)*

During the next step, publications that did not address one of the research questions were not considered further, after reading the whole publications. Here the authors have decided. If the same paper was mentioned several times, the paper was only considered once.

To understand the whole source selection process in detail, it is important to know the number of publications that were considered and not considered. 160 publications were in the initial source selection process. 53 publications are not further considered after reading the abstract and title. After that, some publications are not further considered after reading the whole paper. The 9 final publications are shown in the right arrow of Figure 2. The success factors that were found in these papers were the input for the sorting procedure. The concrete numbers of publications are shown in Figure 2.

It is also important to understand the selection decisions in detail. Some publications were not considered further, because they did not address the research question.

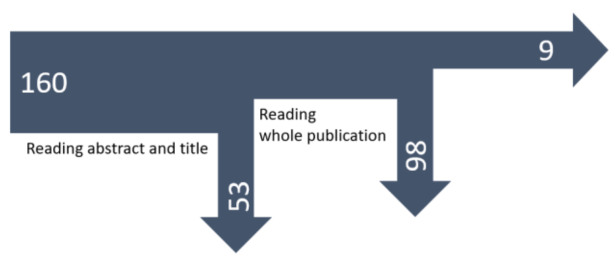

Figure 2. Source Selection Flow with Numbers of Publications

We would like to give some concrete examples, to clarify the meaning of the criteria “not addressing the research questions”: For instance, a publication was not considered after reading the title and the abstract, because neither in the abstract nor title, the term “business model” or a paraphrased description that the paper will lead in the direction of business models was found [25]. Therefore, the publication was not considered in the next step, because it did not address the research questions that focused on business models.

To clarify the criteria “not addressing the research questions”, it is important to give one example in more

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detail: A publication was not considered after reading the abstract and title, because neither in the abstract nor title, the term "success factors" or a paraphrased description that the paper will lead in the direction of success factors was identified here [26]. That is the reason, why the publication was not considered in the next step because it did not address the research questions that focused on success factors models.

The chosen publications address the important parts of the research questions, like business models, success factors, and the mentioned business model types. It is mentioned directly as a term or in a paraphrased description. After the described selection process, the success factory of the final chosen publication was the input for the sorting procedure.

C. Sorting Procedure and Evaluation

Table II includes the sustainable business model success factors in bolt letters in the first column. Table III contains the digital business model success factors in bolt letters in the first column. The second column in both tables contains the references to the publications from which the success factors were taken.

If similar factors for digital and sustainable business models were found, they were labeled with the same red, italic letter. Here, factors with similar content direction were labeled with the same letter. Just to give an example the factor "people and culture" and the factor "Innovative culture" address a similar direction, because there is a focus on the topic of culture. That is why those factors and other similar factors were labeled with the letter A [9][27].

The methodology here is, therefore, based on conventional searching of the overlapping factors. To clarify the sorting results, they are also shown in Figure 3. The figure shows in the left, yellow area the success factors that are mentioned for sustainable business models. The right, blue area includes the success factors for digital business models. It was possible to categorize the factors mentioned exclusively for one type of business model and those applicable to both types. The results need practical evaluation for example in a living lab test, which is described in the discussion section.

III. RESULTS

In this section, the results of the literature review are introduced according to the research question, that they are addressing.

RQ1: Which success factors of digital and/or sustainable business models can be identified

The review clarifies, that it is possible to find success factors for digital and/or sustainable business models. These factors are shown in Figure 3. The success factors that were found are for example: A "Desired social and environmental vision" is needed: This factor was for example mentioned for companies in the social context that want to realize circular economy principles [28].

It is noticeable that the success factors are not positioned in only one thematic direction; it is more a broad range of topics that are mentioned. There are, for example, factors from the economic field, such as "finance" or "leadership", factors from the technical field, like "technology" or "mastery of technology" and other fields.

There are also factors that can be assigned to the software engineering domain, such as "Easiness to use the e-business products and services" [29]. The factors that were found and especially the factors fields that were mentioned several times can be evaluated in more detail in living lab tests in the future.

RQ2: Which success factors of question 1 are mentioned exclusively in one type of business model?

Figure 3 presents the factors that are mentioned exclusively for sustainable business model types in the left, yellow area. Exclusively means in this context, that these factors are mentioned in publications that focus only on one of the business model types, and the other one is not mentioned. For example, "easiness to use" was one of the mentioned success factors for digital business models. This factor can be found to be a success factor in the e-business field [29].

Here it is noticeable that the factors that are mentioned exclusively for sustainable business models are also not only positioned in one thematic direction. There are, for example, factors in the product field, like "Product design" and "Product-Service Systems", but also in the stakeholder field, like "Stakeholder perspective" or "internal employees as key partners". It is also noticeable that there are several factors in the field of stakeholder topics.

In addition, it is noteworthy that the factors that were found for digital business models also do not focus on only one thematic field. There are, for example, factors in the direction of decision-making, like "Risk-taking decision maker", and on the economic field, like "competitive pressure". The success factors that were mentioned can be evaluated in more detail in living lab tests in the future.

RQ3: Which of the success factors defined in question 1 apply to both business model types, for sustainable and digital?

TABLE II. SUCCESS FACTORS FOR SUSTAINABLE BUSINESS MODELS

Factor	Reference	*Overlapping Factor with the other Business Model Type*
Product design	[9]	
Product-service systems	[9]	
People & culture	[9]	*A: People and Culture*
Implementation	[9]	

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process		
Transparency	[9]	
Technology	[9]	*B: Technology*
Ecosystem	[9]	
Customers	[9]	*C: Customers*
Government	[9]	*D: Government*
Desired social and environment vision	[28]	
Value proposition	[28], [30]	*H: value focus*
Alignment of organization to the strategy and acceleration of change through executive leadership implication	[28]	*E: Leadership*
Financial sustainable perspective	[28]	*F: Finance perspective*
Stakeholders perspective	[28]	
Internal process perspective	[28]	
Resources perspective	[28]	
Offering and complementary services	[31]	
Internal employees as key partners and key resources	[31]	
Financing sources	[31]	*F: Finance perspective*
Actions of reorganization	[31]	
Awareness of customer segmentation	[31]	*C: Customers*
Environmental concern	[32]	
Knowledge	[32]	*G: Knowledge*
Logistics/proximity	[32]	
Partnerships	[32]	
Subsidies/participation in development projects	[32]	*F: Finance perspective*
Civil society and consumer requirements	[32]	*C: Customers*
Availability of resources	[32]	
Innovation	[33]	
Value delivery	[30]	*H: value focus*
Value creation	[30]	*H: value focus*

TABLE III. SUCCESS FACTORS FOR DIGITAL BUSINESS MODELS

Factor	Reference	*Over-lapping Factor with the other Business Model Type*
Secured transactions between the company and its customer	[29]	*C: Customers*
Management's commitment to the e- business development	[29]	*E: Leadership*
Easiness to use the e-business products and services	[29]	
Value creation	[34]	*H: value focus*
Value delivery	[34]	*H: value focus*
Value capture dimensions	[34]	*H: value focus*
E promotion and sensitization of digital transformation	[34]	
Suitable platform architecture and strategic	[34]	

judgement of platform providers		
Promotion of a startups culture	[34]	*A: People and Culture*
Risk-taking of decision maker	[27]	
Field experience	[27]	
Technical knowledge	[27]	*G: Knowledge*
Strategic decision	[27]	
Government support	[27]	*D: Government*
Competitive pressure	[27]	
Related regulations	[27]	
AI technology maturity	[27]	*B: Technology*
Mastery of technology	[27]	
Financial investment	[27]	*F: Finance perspective*
Technology quality	[27]	*B: Technology*
Patent protection	[27]	
Reward and recognition	[27]	
Innovative culture	[27]	*A: People and Culture*
Dynamic capability	[27]	

The overlapping area in the middle of Figure 3 includes overlaying factors of the two business model types. Furthermore, they are also shown in red letters in Tables 3 and 4. To give an example of one of these factors:
"People & Culture": This factor was mentioned, for example, for enterprises that transform from a linear to a circular business model. This contains for example topics like agility and mindset transformation [9].

The factors that are mentioned for both business model types are also from different thematic fields, like for example Leadership, Finance Perspective, and Government. The factors that were found and especially the factors fields that were mentioned several times can also be evaluated in more detail in living lab tests in the future.

Table 3 clarifies the success factors for sustainable business models. The first column of the table contains the success factors that were mentioned for sustainable business models in the selected articles. The references of those articles are shown in the second column. The third column included the factors that overlap with the success factors of the digital business model type.

Table 4 includes the success factors for digital business models. The first column of the table contains the success factors that were mentioned for digital business models in the selected articles. The references of those articles are shown in the second column. The third column includes the factors that overlap with the success factors of the sustainable business model type.

For the quantitative evaluation part, it was counted how often the overlapping general factors were found. The result was as follows: People and Culture (3), Technology (3), Customers (4), Government (2), Leadership (2), Finance perspective (4), Value focus (6), and Knowledge (2).

To understand the success factors, it is also important to know the processes, works, or areas in which they occur and in which they can be adapted. Not all of them can be described in depth here, but to explain the topic for one factor in more detail: In [28], criteria are proposed for social enterprises that pursue the goal of applying CE practices. The criteria do not altogether belong to one specific process but to several company topics. For example, financial, resource-related, or strategic aspects are considered. [28]

IV. CONCLUSION AND DISCUSSION

The main findings of this paper are the success factors that were found. Here factors were found that were mentioned for only one of the business model types, for example only for sustainable or only for digital. In addition, factors were found, that were mentioned for both business model types, digital and sustainable. The core of this paper consists of a literature review that was carried out to clarify which success factors can be found for digital and sustainable business models and whether these are factors that are exclusively only suitable for one type of business model or for both business model types.

It was possible to find success factors in the literature in general, for example, "Transparency" [9]. It was also possible to find factors that were only mentioned for one specific business model type. Exclusive digital business model factors were mentioned, for instance, "Mastery of technology" and exclusively sustainable business model factors, like "Product-service systems" [9][27].

Furthermore, success factors were found that can be applied to both types of business models, for instance, factors that include the topic “culture” are sorted into the general factor “People and Culture” [9][27].

different sustainable and digital business models. A living lab is in this context a test area that is used to test new and innovative models under realistic conditions [35].

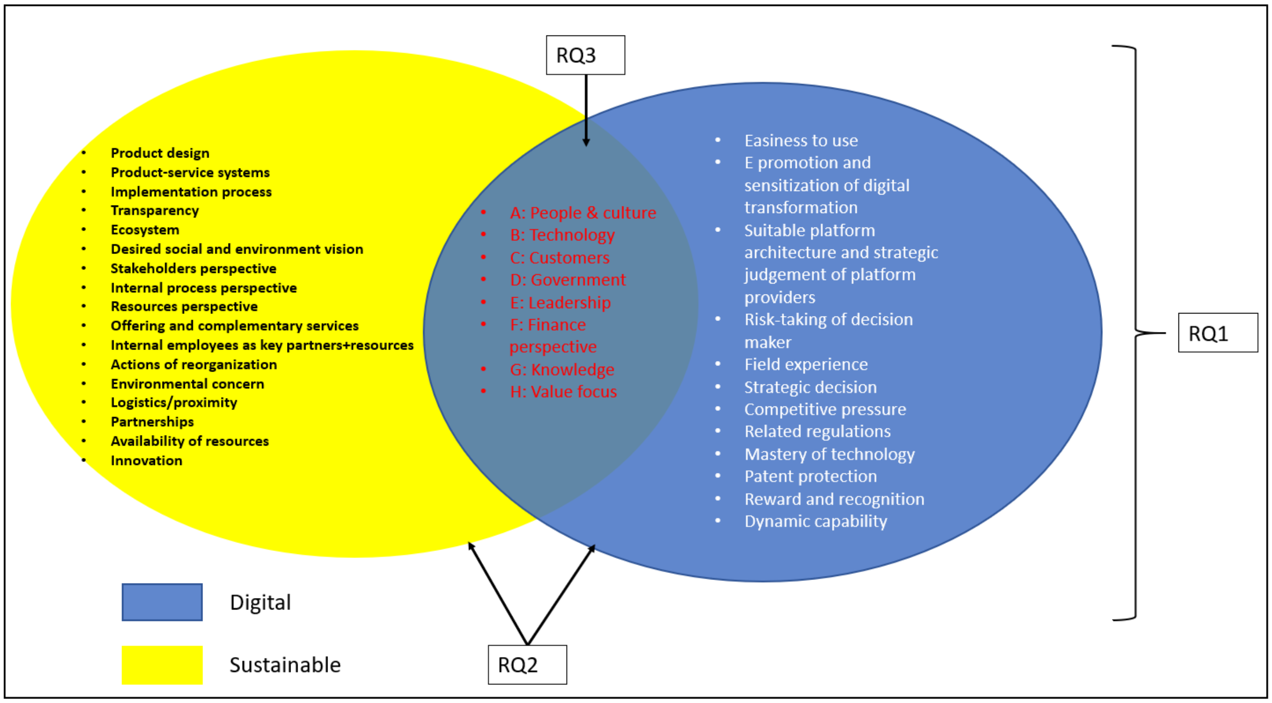

Figure 3. Business Model Success Factors Overview

In total 8 general overlapping factors were found: People and Culture, Technology, Customers, Government, Leadership, Finance perspective, Value focus, and Knowledge. In further literature studies, additional information can be included in the analysis, such as company size, company location, success definition or abstraction level of the success factors, and more publications in the future.

In addition, it is possible to focus on how the factors affect each other. Therefore, the question arises whether the factors can also be related to other business model types. This could be investigated in further work.

One idea for improving the results would be to use more new technologies, for example, the decisions made by the authors could be replaced by decisions based on AI. Furthermore, the review could be repeated in the future if more sources on the topic have been published.

The provided information in this paper is for scientific and informational purposes only and does not constitute a recommendation for action. The next step is to evaluate a selection of these factors in living labs and simulations to see whether the positive effects of these success factors can also be observed in different practical scenarios and for

Here, the same business models could first be tested without consideration of specific success factors and afterward with consideration of those factors. The results can be used to test whether the factor has an effect. This kind of test could be repeated for different business models. In addition, the results of the living lab tests can support entrepreneurs by identifying success factors that they could consider during the design, innovation, or implementation processes of their own business models under consideration of the business model type.

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A Control Framework for Direct Adaptive State and Input Matrix Estimation with Known Inputs for LTI Dynamic Systems

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***Abstract*—Equations Of Motion (EOM) can effectively describe the true physical dynamics within a set of assumptions and constraints. However, in many dynamic systems, the true physical system can deteriorate over time, leading to altered performance as the system ages and is utilized. These physical changes can be characterized as alterations in the constitutive contents and internal interactions. If these health changes are not accounted for in the EOM, discrepancies may emerge between the physical and the model responses. The proposed control scheme examines the case where the true system's plant and input matrix may experience a form of health change. The control scheme depends on knowing the true system's input and output state. The Lyapunov stability proof guarantees internal and external state error convergence to zero asymptotically if the true system experiences health changes within the assumptions and constraints of the proposed control scheme.**

Keywords-Adaptive; Control; Estimation; Plant; Input Matrix.

I. INTRODUCTION

Equations Of Motion (EOM) can describe the dynamics of the true physical system within a set of assumptions and constraints. However, dynamic systems may experience degradation over time or with usage. Failing to account for any deterioration resulting from changes in internal interactions or constitutive constants—such as mass, stiffness, and damping in mechanical systems—can lead to an inaccurate depiction of the true dynamics. Additionally, the potential decline in the system's actuator, which influences how inputs interact with the physical system, is often overlooked. As substantial portion of control problems involves regulating output error concerning a given input. Ignoring the health status changes in system dynamics or actuation can result in catastrophic failure if synthesized inputs do not adequately address these changes.

For traditional Luenberger or Kalman-like estimators to be practical, there has to be minimal uncertainty about the system [1][2]. Unlike Luenberger Estimators, Kalman-like filters are renowned for their ability to eliminate noise and stochastic variations resulting from sensor or process disturbances, under the assumption that the noise follows a Gaussian distribution centered around zero. However, neither type of estimator is capable of accommodating changes in the health status of the system dynamics or the input matrix.

The sensitivity of Luenberger and Kalman-like estimators to minimal uncertainty regarding system dynamics motivates the development of robustness techniques to address model uncertainty [3][4]. The control technique proposed here can manage both plant and input matrix uncertainties. More importantly, it can also accommodate significant changes in system health, as defined in the derivation. This work builds upon our earlier findings, which indicated that only the true-physical plant experiences a health status change, causing changes in dynamics and constitutive constants [5]. In 2022, *Griffith* developed a closed-loop approach for input matrix estimation [6]. This paper explores the scenario in which the plant and the input matrix experience a change in health.

The implemented control architecture was designed for a general system and can be applied to any system that meets the assumptions and constraints outlined in the proof. The proof relies on two primary stability criteria: Strict Positive Real (SPR) and Almost Strictly Dissipative (ASD). For a more formal definition and detailed explanation of SPR and ASD in the context of stability, please refer to [5][7]. Moreover, since none of the estimated states are fed back to the true system, the estimator can operate without risking harm to the true system. Additionally, the proposed control scheme can be utilized offline and online.

Following the introduction, this paper is divided into two main sections: III. Main Result and IV. Illustrative Example. The beginning of Section III offers a summary of the derivation process, presenting this paper's theorem and control diagram. Sub-Sections III-A and III-B provide the assumptions and constraints for both the true and reference systems while laying the foundation for updating the reference model. Sub-Section III-C defines the error states and their dynamics. In error dynamics, residual terms exist; therefore, error states cannot be guaranteed to converge to zero. To address this issue, the error dynamics are treated as energy-like terms. Then, an energy-like balance is constructed to remove residual terms, guaranteeing the error state to converge to zero globally as time approaches infinity. This process is detailed in Section III-D and III-E. Following the derivation, Section IV. Illustrative Example details the implementation of the derived control scheme. This example details a generic system where the error states converge to zero. The interaction tuning terms $\{\gamma_u, \gamma_u\}$ were left unadjusted in the example. However, tuning these terms can impact the time the error state converges.

II. Nomenclature

A	=	True Plant
A_m	=	Model Plant
ASD	=	Almost Strictly Dissipative
B	=	Input Matrix
B_m	=	Input Matrix Model
$\in$	=	Belongs
C	=	Output Matrix
$(\cdot)^\dagger$	=	Conjugate Transpose
e_x	=	Internal State Error
$\hat{e}_y$	=	External State Error
$\hat{}$	=	Estimate
$\forall$	=	For All
L_*	=	Fixed Correction Matrix
γ	=	Interaction Tuning Term
ΔL	=	Variance Matrix
PR	=	Positive Real
SPR	=	Strictly Positive Real
σ	=	Set of Eigenvalues
$\ni$	=	Such that
Re	=	Real
$\exists$	=	There Exists
u	=	Input
x	=	Internal State
y	=	External (Output) State

III. Main Result

Pertaining to the work being presented, the derived theorem and control laws, shown in Theorem 1 and Figure 1, are catered to minimizing the internal state error (e_x) to zero between true-physical system and reference model. This is achieved by accounting for discrepancies in the model plant (A_m) and input matrix (B_m), given a known input (u), output matrix (C), and external state (y). Uncertainty or variability in the model plant and input matrix means the convergence of the internal state error to zero cannot be guaranteed. As detailed in the derivation, to mitigate any variability, the error system is treated as an energy-like term. The aim is to dissipate all the energy of the error system, thereby ensuring the internal state error converges to zero as time approaches infinity, $e_x \xrightarrow[t\to\infty]{} 0$. To ensure error energy-like dissipation, the energy-like time rate of change for the error system is determined. Subsequently, residual energy-like time rate of change terms from any uncertainty are identified and countered. The remaining energy-like time rate of change term and the use of stability lemma, Barbalat-Lyapunov Lemma, ensures $e_x \xrightarrow[t\to\infty]{} 0$ asymptotically.

Theorem 1: Output Feedback on Reference Model for Adaptive Input Matrix, Plant, and State Estimation.

Consider the following state error system:

$$\begin{cases} \dot{e}_x = (A_m - KC)e_x + B_m\left(\Delta L_1 u + \Delta L_2 y\right) \\ \hat{e}_y = Ce_x = C(\hat{x} - x) \\ L_1 = \Delta L_1 + L_{1*} \\ L_2 = \Delta L_2 + L_{2*} \\ \dot{L}_1 = \Delta\dot{L}_1 = -e_y u^\dagger \gamma_u \\ \dot{L}_2 = \Delta\dot{L}_2 = -e_y y^\dagger \gamma_y \end{cases}, \quad (1)$$

where e_x is the estimated internal state error, $\hat{e}_y$ is the external estimated state error, $\{L_{1*}, L_{2*}\}$ are fixed-correction matrices, $\{\Delta L_1, \Delta L_2\}$ are the variability-uncertainty terms, K is a fixed gain, and $\{\gamma_u, \gamma_y\} > 0$ are interaction tuning terms. Given:

1) The triples of (A, B, C) and (A_m, B_m, C) are ASD and SPR respectively.
2) A model plant (A_m) must exist.
3) A model input matrix (B_m) must exist.
4) Output matrix (C) is known.
5) Allow $B \in \text{Sp}\{B_m L_{1*}\} \ni B \equiv B_m L_{1*}$.
6) Allow $A \in \text{Sp}\{A_m, B_m L_{2*} C\} \ni A = A_m + B_m L_{2*} C$.
7) The set of eigenvalues (σ) of the true and reference plant are stable (i.e. $\text{Re}(\sigma(A)) < 0$ & $\text{Re}(\sigma(A_m)) < 0$).

If conditions are met, then $\{e_x, \hat{e}_y\} \xrightarrow[t\to\infty]{} 0$ asymptotically. $\{\Delta L_1, \Delta L_2\}$ are guaranteed to be bounded; however, no guarantee of $\{\Delta L_1, \Delta L_2\} \xrightarrow[t\to\infty]{} 0$. If $\{\Delta L_1, \Delta L_2\} \xrightarrow[t\to\infty]{} 0$, then the dynamics of the true system or some energy equivalence have been numerically captured.

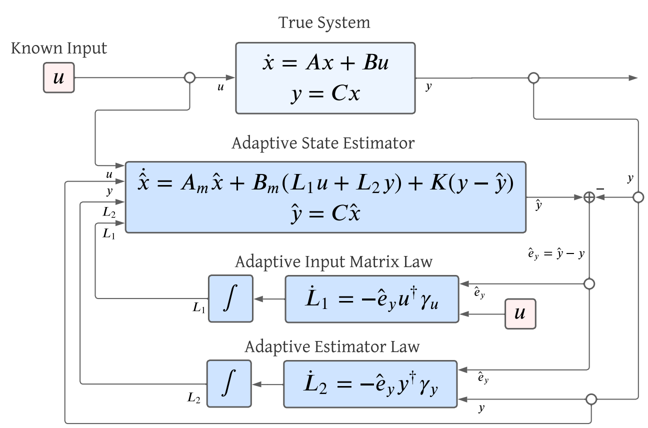

Figure 1. Control diagram for adaptive plant, input matrix, and state estimation given a known input (u), output matrix (C), and external state (y).

A. Defining True System Dynamics

Assume the dynamics of the true-physical system is linear time-invariant and therefore can be expressed in state-space form such that:

$$\text{True System} \begin{cases} \dot{x} = Ax + Bu \\ y = Cx. \end{cases} \quad (2)$$

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Both the true system's plant (A), assumed to be stable (i.e. $\text{Re}(\sigma\{A\}) < 0$), and the input matrix (B) experience a health change caused by age or use, altering the constitutive constants and system dynamics. Output matrix (C) and external (output) state (y) are known. The input (u) can be any bounded-continuous waveform the user provides, possibly a known disturbance.

B. Overview of Updating the Reference Model

Subsequent sections will derive a control scheme and laws to minimize the error between the true and reference systems, (2) and (3), respectively. Note that both true and model systems match in dimension size.

$$\text{Reference Model} \begin{cases} \dot{x}_m = A_m x_m + B_m u \\ y_m = C x_m \end{cases} \tag{3}$$

To update the input matrix model (B_m), assume that B_m can be corrected via a input matrix fixed correction term (L_{1*}) such that:

$$B \equiv B_m L_{1*}. \tag{4}$$

The true plant is assumed to be decomposed into two components: an initial model (A_m) and plant matrix correction term $(B_m L_{2*} C)$ such that:

$$A \equiv A_m + B_m L_{2*} C. \tag{5}$$

Both (4) and (5) assumed decompositions are structured such that they can modified via an estimator. In the estimator, the initial input matrix and plant are updated via their respective correction term $\{L_1, L_2\}$:

$$L(t) = \Delta L + L_* \xrightarrow[t\to\infty]{} L(t) = L_*, \tag{6}$$

where ΔL is the variability-uncertainty term. If both variability term converges to zero, $\{\Delta L_1, \Delta L_2\} \xrightarrow[t\to\infty]{} 0$, then the input matrix and true plant (or energy equivalent) have been numerically captured. For the control scheme to apply, the true and reference systems must be ASD and SPR, respectively.

C. Estimated State Error

Given that the true plant (A) and input matrix (B) experiences a health change caused by age or use and the internal state (x) is often blended into a linear combination or missing from the external state (y), an estimator can be created using the reference model:

$$\text{Estimator} \begin{cases} \dot{\hat{x}} = A_m \hat{x} + B_m (L_1 u + L_2 y) \\ \hat{y} = C\hat{x}. \end{cases} \tag{7}$$

To minimize the error between the true and estimated systems, consider the following error state equations:

$$\begin{cases} e_x = \hat{x} - x \\ \hat{e}_y = \hat{y} - y = C e_x. \end{cases} \tag{8}$$

To capture the internal state of the true system, the internal state error must converge to zero as time approaches infinity. To investigate the internal state error dynamics, take the time derivative of the internal state error and substitute (2) and (7):

$$\begin{aligned} \dot{e}_x &= \dot{\hat{x}} - \dot{x} \\ &= A_m \hat{x} + B_m (L_1 u + L_2 y) - (Ax + Bu). \end{aligned} \tag{9}$$

From (9), consider the difference between input matrices:

$$\begin{aligned} B_m (\underbrace{\Delta L_1 + L_{1*}}_{=L_1}) u - \underbrace{B_m L_{1*}}_{=B} u &= B_m \underbrace{\Delta L_1 u}_{=w_u} \\ &= B_m w_u. \end{aligned} \tag{10}$$

Again, using (9) as a reference, consider the difference between the model and true plants, where $A \equiv A_m + B_m L_{2*} C$:

$$\begin{aligned} A_m \hat{x} + B_m (\underbrace{\Delta L_2 + L_{2*}}_{=L_2}) y - Ax =& A_m e_x + B_m \underbrace{\Delta L_2 y}_{=w_y} \\ =& A_m e_x + B_m w_y. \end{aligned} \tag{11}$$

Therefore, the error system can be written as:

$$\begin{cases} \dot{e}_x = A_m e_x + B_m (w_u + w_y) \\ \hat{e}_y = C e_x. \end{cases} \tag{12}$$

Additionally, the estimator can be extended to use a fixed gain (K):

$$\begin{cases} \dot{\hat{x}} = A_m \hat{x} + B_m (L_1 u + L_2 y) + K(y - \hat{y}) \\ \hat{y} = C\hat{x}. \end{cases} \tag{13}$$

Resulting in the following error equation:

$$\begin{cases} \dot{e}_x = (\underbrace{A_m - KC}_{=A_c}) e_x + B_m (w_u + w_y) \\ \hat{e}_y = C e_x. \end{cases} \tag{14}$$

To use (14), find a fixed gain $(K) \ni \text{Re}(\sigma\{A_m - KC\}) < 0$.

Regardless of the estimator selected, the internal state error (e_x) can not be guaranteed to converge such that $e_x \xrightarrow[t\to\infty]{} 0$ due to the residual terms $\{w_u, w_y\}$ existing in the error equation. To adequately address these residual components, additional considerations are needed.

D. Lyapunov Stability for the Estimated State Error

Lyapunov stability analysis represents dynamic systems in terms of energy-like functions to describe the convergence of a particular or a set of states. For this case study, Lyapunov stability is used to guarantee the convergence of internal state error $(e_x) \ni e_x \xrightarrow[t\to\infty]{} 0$.

Given the state error equation as described in Eq.(12), consider the following energy-like Lyapunov equation with assumed real scalars:

$$V_e = \frac{1}{2} e_x^{\dagger} P_x e_x; P > 0, \tag{15}$$

where the $(\cdot)^{\dagger}$ is the conjugate transpose operator and where $P > 0$ represents a matrix P that is symmetric $(P_x = P_x^{\dagger})$ and positive-definite $\text{Re}(\sigma\{P_x\}) > 0$.

To determine the energy-like time rate of change of V_e, take the time derivative of V_e and substitute (12) for the error dynamics:

$$\begin{aligned}2\dot{V}_e =&\dot{e}_x^\dagger P_x e_x + e_x^\dagger P_x \dot{e}_x \\ =&(A_m e_x + B_m(w_u + w_y))^\dagger P_x e \\ &+ e_x^\dagger P_x (A_m e_x + B_m(w_u + w_y)) \\ =&e_x^\dagger (A_m^\dagger P_x + A_m P_x) e_x + 2\underbrace{e_x^\dagger P_x B_m (w_u + w_y)}_{=(B_m(w_u+w_y))^\dagger P_x e_x}.\end{aligned} \tag{16}$$

Modifying SPR stability condition for the reference model:

$$\begin{cases} A_m^\dagger P_x + P_x A_m = -Q_x \\ P_x B_m = C^\dagger \end{cases} ;Q_x > 0. \tag{17}$$

From here, the SPR condition can be applied to (16), resulting in:

$$\begin{aligned}2V_e &= -e_x^\dagger Q_x e_x + 2\underbrace{e_x^\dagger C^\dagger}_{=\hat{e}_y^\dagger}(w_u + w_y) \\ &= -e_x^\dagger Q_x e_x + 2\hat{e}_y^\dagger w_u + 2\hat{e}_y^\dagger w_y \\ &= -e_x^\dagger Q_x e_x + 2\underbrace{(\hat{e}_y, w_u)}_{=(w_u,\hat{e}_y)} + 2\underbrace{(\hat{e}_y, w_y)}_{=(w_y,\hat{e}_y)}.\end{aligned} \tag{18}$$

By removing the residual terms $\{(\hat{e}_y.w_u), (\hat{e}_y, w_y)\}$ in (18), results in $V_e \le 0$.

To counter the residual terms, consider the following energy-like functions:

$$V_u + V_y = \frac{1}{2}\text{tr}(\Delta L_1 \gamma_u^{-1} \Delta L_1^\dagger) + \frac{1}{2}\text{tr}(\Delta L_2 \gamma_y^{-1} \Delta L_2^\dagger), \tag{19}$$

where $\{\gamma_u, \gamma_y\} > 0$. The energy-like time rate of change for $V_u + V_y$ follows:

$$\dot{V}_u + \dot{V}_y = \underbrace{\text{tr}(\Delta \dot{L}_1 \gamma_u^{-1} \Delta L_1^\dagger)}_{=\text{tr}(\Delta L_1 \gamma_u^{-1} \Delta \dot{L}_1^\dagger)} + \underbrace{\text{tr}(\Delta \dot{L}_2 \gamma_y^{-1} \Delta L_2^\dagger)}_{=\text{tr}(\Delta L_2 \gamma_y^{-1} \Delta \dot{L}_2^\dagger)}. \tag{20}$$

A control law for the input matrix and plant variance time rate of change $\{\Delta \dot{L}_1, \Delta \dot{L}_2\}$ can be defined as the following:

$$\begin{cases} \Delta \dot{L}_1 = -e_y u^\dagger \gamma_u \\ \Delta \dot{L}_2 = -e_y y^\dagger \gamma_y. \end{cases} \tag{21}$$

Substituting (21) into (20):

$$\begin{aligned}\dot{V}_u + \dot{V}_y =&\text{tr}(\underbrace{-e_y u^\dagger \gamma_u}_{\Delta \dot{L}_1} \gamma_u^{-1} \Delta L_1^\dagger) \\ &+ \text{tr}(\underbrace{-e_y y^\dagger \gamma_y}_{\Delta \dot{L}_2} \gamma_y^{-1} \Delta L_2^\dagger) \\ =&-\text{tr}(e_y \underbrace{u^\dagger \Delta L_1^\dagger}_{=w_u^\dagger}) - \text{tr}(e_y \underbrace{y^\dagger \Delta L_2^\dagger}_{=w_y^\dagger}) \\ =&-\text{tr}(e_y w_u^\dagger) - \text{tr}(e_y w_y^\dagger) \\ =&-\text{tr}(w_u^\dagger e_y) - \text{tr}(w_y^\dagger e_y) \\ =&-w_u^\dagger e_y - w_y^\dagger e_y \\ =&-(w_u, e_y) - (w_y, e_y).\end{aligned} \tag{22}$$

For notation purposes, allow the following:

$$\begin{cases} V_{euy} = V_e + V_u + V_y \\ \dot{V}_{euy} = \dot{V}_e + \dot{V}_u + \dot{V}_y. \end{cases} \tag{23}$$

From here, the estimate state error closed-loop energy-like function can be written as:

$$\begin{aligned}V_{euy} =&\frac{1}{2}e_x^\dagger P_x e_x + \frac{1}{2}\text{tr}(\Delta L_1 \gamma_u^{-1} \Delta L_1^\dagger) \\ &+ \frac{1}{2}\text{tr}(\Delta L_2 \gamma_y^{-1} \Delta L_2^\dagger).\end{aligned} \tag{24}$$

Therefore, the estimated state error closed-loop energy-like time rate of change can be written as:

$$\begin{aligned}\dot{V}_{euy} =&-\frac{1}{2}e_x^\dagger Q_x e_x + (w_u, \hat{e}_y) + (w_y, \hat{e}_y) \\ &-(w_u, \hat{e}_y) - (w_y, \hat{e}_y) \\ =&-\frac{1}{2}e_x^\dagger Q_x e_x \le 0.\end{aligned} \tag{25}$$

Having $\dot{V}_{euy} \le 0$ means that $\{e_x, \Delta L_1, \Delta L_2\}$ are guaranteed to be bounded. Due to $\dot{V}_{euy}$ negative-semi-definite nature, no additional information can be said about the error internal state (e_x) converging $\ni e_x \xrightarrow[t\to\infty]{} 0$.

E. Applying Barbalat-Lyapunov Lemma on $\dot{V}_{euy}$

To guarantee $e_x \xrightarrow[t\to\infty]{} 0$, consider Barbalat-Lyapunov Lemma - Given:

1) V is lower bounded.
2) $\dot{V}$ is negative-semi-definite.
3) $\dot{V}$ is uniformly continuous in time.

If all conditions are met, then $\dot{V} \xrightarrow[t\to\infty]{} 0$ according to [8].

The first two conditions of Barbalat-Lyapunov Lemma are satisfied with (24) and (25). The third condition, $\dot{V}_{euy}$ being uniformly continuous in time and can be satisfied by showing that $\ddot{V}_{euy}$ is bounded [8].

To prove $\ddot{V}_{euy}$ is bounded, consider W_{euy}:

$$W_{euy} \ge -\dot{V}_{euy} \ge 0. \tag{26}$$

Taking the time derivative of W_{euy} results in the following:

$$\begin{aligned}\dot{W}_{euy} =&2e_x^\dagger Q_x \dot{e}_x \\ =&2e_x^\dagger Q_x (A_m e_x + B_m(w_u + w_y)) \\ =&2e_x^\dagger Q_x (A_m e_x + B_m(\Delta L_1 u + \Delta L_2 y)).\end{aligned} \tag{27}$$

From (25), $\{e_x, \Delta L_1, \Delta L_2\}$ are bounded. Input (u) can be any bounded-continuous waveform. Following, the true plant is assumed stable ((i.e., $\text{Re}(\sigma\{A\}) < 0$); therefore, a bounded input will result in a bounded output (y) [9]. Combining all bounded results yields: $\dot{W}_{euy}$ is indeed bounded. Making $\ddot{V}_{euy}$ bounded.

Given that all the conditions of Barbalat-Lyapunov are satisfied, $\dot{V}_{euy}$ evolution in time can be expressed as:

$$\dot{V}_{euy} \xrightarrow[t\to\infty]{} 0. \tag{28}$$

Therefore, proves $e_x \xrightarrow[t\to\infty]{} 0$ is asymptotically guaranteed. However, regardless of Barbalat-Lyapunov being satisfied, Lyapunov stability results only guarantees $\{\Delta L_1, \Delta L_2\}$ to be bounded. If $\{\Delta L_1, \Delta L_2\} \xrightarrow[t\to\infty]{} 0$ numerically, the true input matrix and plant or an energy equivalence have been captured. Additionally, without loss of generality, derived Lyapunov stability proof can be modified for the error system using fixed gain, Eq. (12).

Altogether, assuming the reference (A_m, B_m, C) and true (A, B, C) systems are SPR and ASD respectfully, such that the decomposition of the true input matrix (B) and plant (A) can be written as $B \equiv B_m L_{1*}$ and $A \equiv A_m + B_m L_{2*} C$. Then adaptive laws (Eq. (21)) and diagram (Figure 1) can be formulated such that the internal state error is guaranteed to converge zero asymptotically. Lyapunov stability proof only guarantees that $\{\Delta L_1, \Delta L_2\}$ will be bounded. However, if $\{\Delta L_1, \Delta L_2\} \xrightarrow[t\to\infty]{} 0$, then the true input matrix and plant or energy equivalent have been numerically captured.

IV. Illustrative Example

The following is an illustrative example of applying Theorem 1 and the control diagram (Figure 1) on a general case study. Numerical values for (A_m, B_m, C) and (A, B, C) are derived and modified from [10].

A. State Space Representations for Reference and True Systems

Allow the reference model as defined in (3) have the following properties:

$$\begin{aligned} A_m &= \begin{bmatrix} -7 & 2 & 4 \\ -2 & -1 & 2 \\ -2 & 2 & -1 \end{bmatrix}; \\ B_m &= \begin{bmatrix} 0 \\ .7 \\ 2 \end{bmatrix}; C = \begin{bmatrix} 0.5 & 0 & 1 \end{bmatrix}; x(0) = 0. \end{aligned} \tag{29}$$

To apply the control scheme as defined in Theorem 1 and show in Figure 1, allow the true system as defined by (2) have the following properties:

1) $B \in \text{Sp}\{B_m L_{1*}\} \ni B \equiv B L_{1*}$.
2) $A \in \text{Sp}\{A_m, B_m L_{2*} C\} \ni A \equiv A_m + B L_{2*} C$.

Assume the health change for the input matrix and plant can be described by $\{L_{1*}, L_{2*}\} \ni L_{1*} = 2$ and $L_{2*} = -5$. Therefore, the true system can be defined by the following:

$$\begin{aligned} A \equiv& A_m + B_m L_{2*} C = \begin{bmatrix} -7 & 2 & 4 \\ -3.75 & -1 & -1.5 \\ -7 & 2 & -11 \end{bmatrix}; \\ B \equiv& B_m L_{1*} = \begin{bmatrix} 0 \\ 1.4 \\ 4 \end{bmatrix}; C = \begin{bmatrix} 0.5 & 0 & 1 \end{bmatrix}; x(0) = 0. \end{aligned} \tag{30}$$

Recall that the constitutive constants of the true plant (A) and input matrix (B) are unknown. However, an initial estimate of the plant (A_m) and input matrix (B_m) exists.

When both the reference and true systems, as defined in (29) and (30), are given a unit step input, as shown in Figure 2, the differences in rise times and output response become evident. These differences can be further explained by examining the eigenvalues of the reference and true plants:

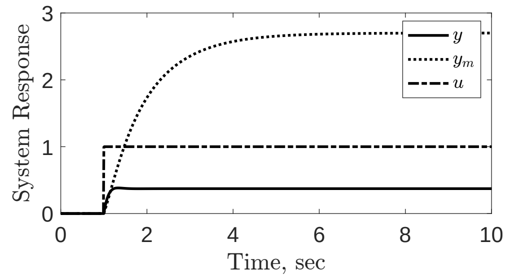

Figure 2. True (y) and reference model (y_m) output response given a unit step input (u).

$$\begin{aligned} \sigma(A_m) &= \{-1, -3, -5\} \\ \sigma(A) &\approx \{-2.28, -8.36 \pm i5.05\}. \end{aligned} \tag{31}$$

B. Defining the Known Input (u)

To implement the control scheme, a bounded and continuous input must be used. In practice, this input can be a known disturbance. For this example, allow the input be defined as:

$$u = 2 + \sin(2t). \tag{32}$$

C. Adaptive Estimation

In this section, the proposed control scheme detailed in Figure 1 is implemented with two cases: with and without the use of a fixed gain (K) term.

1) Adaptive Control Scheme without the use of Fixed Gain $(K = 0)$: The control scheme detailed in Figure 1 is implemented without using the fixed gain term $(K = 0)$ and $\{\gamma_u, \gamma_y\} = I$. As derived in the proof, Figure 3 demonstrates the convergence of the internal state, where $e_x \xrightarrow[t\to\infty]{} 0$. Given that the internal state error converges to zero, equivalently, the external state error convergences $\ni \hat{e}_y \xrightarrow[t\to\infty]{} 0$. Meaning that the estimated output $(\hat{y})$ converges to the true output (y).

Although the proof only guarantees that the adaptive variance will be bounded, numerically $\{\Delta L_1, \Delta L_2\} \xrightarrow[t\to\infty]{} 0$. For this case study, the true input matrix and plant have been numerically captured, Figure 4 and Figure 5.

2) Adaptive Control Scheme with the use of Fixed Gain $(K \neq 0)$: The control scheme detailed in Figure 1 is implemented using the fixed gain term $(K \neq 0)$ and $\{\gamma_u, \gamma_y\} = 1$. The fixed gain term K was derived using a Linear Quadratic Regulator where $Q = I_3$ and $R = 1$. Similarly to the result of Section IV-C1, $e_x \xrightarrow[t\to\infty]{} 0$, shown in Figure 6. Again, since the internal state error converges to zero, the external error will converge to zero for the true and estimator systems. Moreover, as $\{\Delta L_1, \Delta L_2\} \xrightarrow[t\to\infty]{} 0$ the true input matrix and plant are numerically captured in Figures 7 and 8.

There can be benefit of using a fixed gain term in the estimator, as the term can affect the time in which internal states and adaptive terms converge, compare Figure 4 and

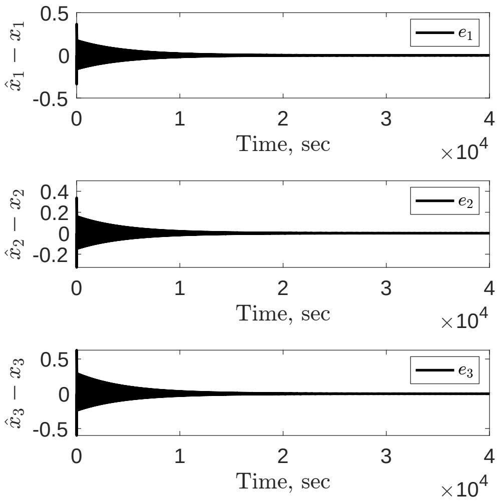

Figure 3. Internal state error converging to zero without the use of the fixed gain ($K = 0$).

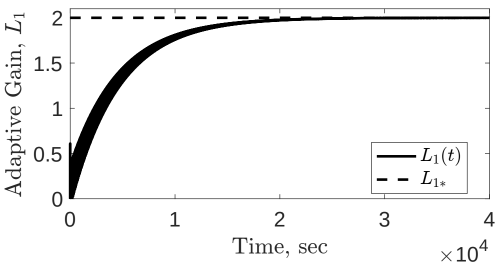

Figure 4. Input Matrix adaptive term $L_1(t)$ converging to L_{1*} without the use of the fixed gain ($K = 0$).

Figure 7. More crucially, both adaptive tuning terms $\{\gamma_u, \gamma_y\}$ can be adjusted to amply or dampen the effects of the adaptive controller, directly impacting the convergence of the error state. For this particular example, setting $\gamma_u = 1.3$ and $\gamma_y = 1.85$ reduces the time in which $e_x \xrightarrow[t\to\infty]{} 0$ and $L \xrightarrow[t\to\infty]{} L_*$ by order of magnitude faster than the depicted figures in this text. However, there are numerical limits for the tuning terms $\{\gamma_u, \gamma_y\}$. Making the adaptive controller too sensitive to changes may lead to divergent artifacts.

V. Conclusion

A physical system can experience wear and tear with use or age, altering performance. This paper examines the case where the true plant and the input matrix undergo a change in health, described as alterations in constitutive constants or internal interactions. If these health changes are not considered in the model, discrepancies in the true and model system dynamics can occur. This work proposes addressing the change in the true system's health by updating the model of the plant and input matrix according to their respective adaptive laws. If the assumptions and constraints of the proof are met, the adaptive laws will ensure that both internal and external state errors converge to zero asymptotically.

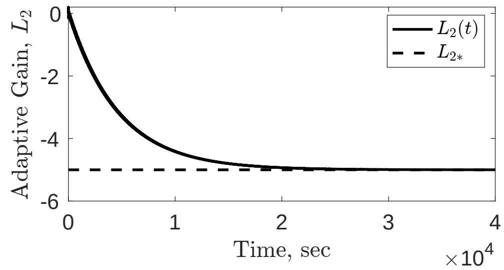

Figure 5. Plant correction adaptive term $L_2(t)$ converging to L_{2*} without the use of the fixed gain ($K = 0$).

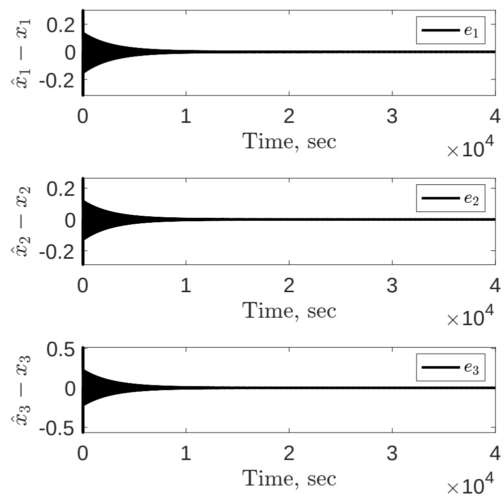

Figure 6. Internal state error converging to zero without the use of the fixed gain ($K \neq 0$).

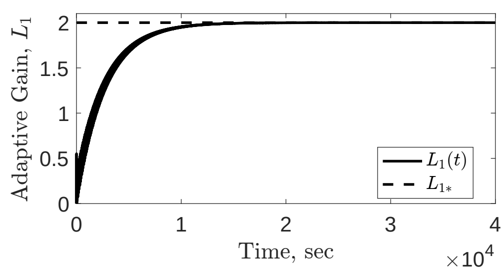

Figure 7. Input Matrix adaptive term $L_1(t)$ converging to L_{1*} with the use of the fixed gain ($K \neq 0$).

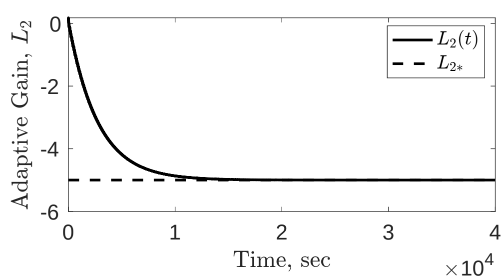

Figure 8. Plant correction adaptive term $L_2(t)$ converging to L_{2*} with the use of the fixed gain ($K \neq 0$).

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Repairing is Caring - An Approach to an AI-Supported Product-Service-System for Bicycle Lifecycle Prolonging

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***Abstract*—Bicycles play an essential role in today's mobility ecosystems and are an important part of future mobility concepts. Bicycles develop defects as a result of frequent use both during and after the operational phase. In some cases, repairing can be a solution to prolong the duration of a bicycle's usage by restoring its condition while simultaneously preventing the generation of new waste. To plan the repair process, it is critical for both the bicycle's owner, referred to as the client, and the repair service provider to determine the defects and whether fixing the problem is worthwhile in this particular situation. Therefore, there is currently a gap in potential solutions for accelerating this process. The paper aims to investigate how Artificial Intelligence (AI) can support repair business models to increase the attractiveness of sustainable, prolonged solutions. Consequently, AI-based experiments were conducted to design two specific classifiers to examine the state of different kinds of bicycles. The AI-based models were trained, validated, and tested in these experiments to develop a product-service-system based on the images of the bicycles and the repair information collected from the repair service provider.**

Keywords*—*Bicycles; Repairing; Product-Service-System; Artificial Intelligence; Circular Economy.

I. INTRODUCTION

The usage of bicycles is already part of current mobility solutions and is a key factor in sustainable mobility concepts of the future. The advantages of using bicycles are, for example, a reduction in the rate of emissions and the requirement for less space compared to other mobility solutions, which is a huge benefit in crowded urban spaces.

During the operational usage of bicycles over their lifetime, the occurrence of defects and damages is natural. For instance, the chain and tires of the bicycle normally have a shorter lifetime than other components due to the stresses afflicted upon them. As an option for prolonging the lifetime of a bicycle as a whole, these components can be exchanged or repaired fairly easily [1].

However, to repair the defects and assess if it is a feasible option for all the stakeholders, this information needs to be apparent. In addition, to decide for both the repair service provider and the client, the key is to identify and analyze the feasibility of a given bicycle properly. Nowadays, this process is still largely performed manually, which is time-consuming and requires an expensive workforce. Therefore, digital AI-based tools paired with the ecosystem could prevent stakeholders from undertaking time or cost-extensive processes to assess bicycles, shorten delays for the spare part delivery, and enable new business models in the field of repairing.

This work aims to address this issue and propose a possible solution for accelerating the respective process. The paper presents AI-based models for two specific use cases, capable of addressing different questions regarding the condition assessment of bicycles. This paper continues the scientific research work already presented by Geger et al. [2]. Additionally, the aspired repair ecosystem is presented, which allows the identified stakeholder to flesh out based on sustainable business models.

The following Sections of the presented paper are structured as follows: Section II describes the Related Work, and Section III presents the suitable Bicycle Repair Ecosystem. Subsequently, Section IV deals with the Scope of the AI support and the Data Recording, followed by the AI-based Methodology presented in Section V. Finally, the paper summarizes the Results and Analysis shown in Section VI, followed by the Challenges and Future Work in Section VII and the Conclusion in Section VIII.

II. RELATED WORK

One way to reduce waste and increase the lifespan of products is to transform from a linear economy to a circular economy. Most approaches to modeling the circular economy define reuse and repairing as the first actions to increase the lifespan of a product, as described in [3]. Therefore, the circular economy not only plays a major role in reducing waste but is also an effective way to create a sustainable ecosystem on a large scale.

When it comes to bicycles, one must decide whether a bicycle can be repaired, whether it is possible to reuse the components, or whether recycling is the best option. Consequently, a service platform is needed to determine which decision is the best for a repair service provider and which for the client. In addition, the platform must consist of the interests of clients and the repairer service providers concerning the circular economy. Blomsma et al. [4] illustrates one such example as they assess different lifecycle options in one system.

Moreover, the application of AI is increasingly crucial in today's world for making various lifecycle-based decisions, which is also a crucial component of the circular economy with the aim of achieving sustainability. One of the popular areas in the field of AI is deep learning. Deep learning utilizes multi-layered neural networks to learn from input data and make decisions. In the field of deep learning, a commonly utilized feedforward neural network is Convolutional Neural Networks (CNNs). CNNs are distinguished from other types of neural networks due to their ability to identify visual features for different tasks in vast amounts of data, as also pointed out by Yamashita et al. [5]. A CNN mainly comprises three types of layers. The Convolutional, Pooling, and Fully Connected Layers (FCLs). These layers can be ordered and utilized in multiple variations. The convolutional and pooling layers are utilized for feature extraction, and the FCL is for classifying the output.

Furthermore, one of the popular CNN-based architectures is InceptionV3 presented by Szegedy et al. [6], which proposed a new standard for classification tasks. In addition, another important strategy in the field of AI is transfer learning, which utilizes the AI-based models already trained on extensive datasets and adapts the output layers to meet the requirements of the new tasks, as described in [7].

In the context of bicycles, the different components of a bicycle are influenced by daily use to varying degrees. For example, a component of a bicycle could contain some rust, and this can be a reason for replacing the respective component. But this is not always true, as it depends on the amount of rust. For instance, Petricca et al. [8] utilized CNNs for rust detection of different products. However, besides the detection of a component condition, it is also interesting to find out about missing components. On the other hand, Zou et al. [9] utilized CNNs to detect missing components of historical buildings. In addition to the detection of components, the assessment of the product as a whole is another interesting area for the use of AI.

Most notably, the key question for the lifecycle assessment is whether a product is repairable or not. Liao et al. [10] investigated the questions by two approaches. One of the approaches was utilizing a supervised learning framework, which uses transfer learning with common machine learning architecture, including ResNet50, ConvNeXt, and VGG16. The other approach builds an unsupervised learning framework, which includes feature extraction and cluster learning with the goal of getting inside of the product design. A smartphone was used as an exemplary product.

However, a product lifecycle decision is necessary for making such a decision. Moreover, Liao et al. [10] emphasize several limitations in their study. The insufficiency of data affects product repairability since it is a multifaceted, intricate issue. Therefore, the author suggests incorporating various datasets in subsequent research. In addition, potential future directions proposed by the authors include evaluating results with expert opinion and considering other business and sustainability factors.

The presented work in this paper utilizes a bicycle dataset that was already created with the definition of the labels by Geger et al. [2]. The existing work presents four different project phases. The collected dataset consists of 115 distinct bicycles with several images taken from different angles and frames for each bicycle. Moreover, the images are labeled according to the Product Breakdown Structure (PBS) [2], defined together with the repair service provider. In addition to the information about each component of the bicycle, where the condition of every component was labeled, it was also labeled if the bicycle in general is repairable or not, based on the assessment of the repairer. Thus, the first phases till the creation of the dataset have been completed, and subsequent steps concerning the training of the AI-based models are presented in this paper.

III. Bicycle Repair Ecosystem

The offer for repair services for in-use goods is already showing an increase in the overall service demand [11]. To enable businesses to participate in this new kind of service environment, service blueprints are an essential enabler in implementing the necessary infrastructure and the corresponding processes. This is especially the case for Small and Medium Enterprises (SMEs) [12], which are in need of adaptable business models and structures.

Regarding a sustainable product-service-system for bicycles, all the participating stakeholders need to be taken into account to offer interfaces for the different service providers. These include, besides the *Client*, the *Repair Service Operator*, the *Digital System Service Operator*, as well as the *Logistics Service Provider*. As shown in Figure 1, the aspired ecosystem for the designed repairing service is depicted with the corresponding interactions between the stakeholders of the system. The different stages of the process are illustrated in Figure 1, marked with green along with the corresponding number of the steps.

To set up the necessary foundation for the repairing process, the *Digital System Service Provider* is responsible for providing the necessary infrastructure in terms of user interface (*App on Client Device*) as well as the pipeline to the backbone of the system, the *AI Server Infrastructure* with its models. Likewise, the Repair Service Provider should distribute his *Repair Assessment Criteria*, the information regarding his criteria on repairability, to the *AI Server Infrastructure*.

Starting with the recording of the defective bicycle, the process is initiated by the client, who is using the *App on Client Device* on his cell phone to capture photos of the damaged bicycle in order to enable the assessment of the damage (Step 1).

After the images are taken, they are sent (Step 2) via the application to the *AI Server Infrastructure*, where the models are hosted by the *Digital System Service Provider*.

The images are then processed in the next stage (Step 3) by the *General CNN Model: Defect Detection* as well as the *Individual CNN Model: Repair Assessment*, which is trained based on the *Repair Service Provider's Repair Assessment*

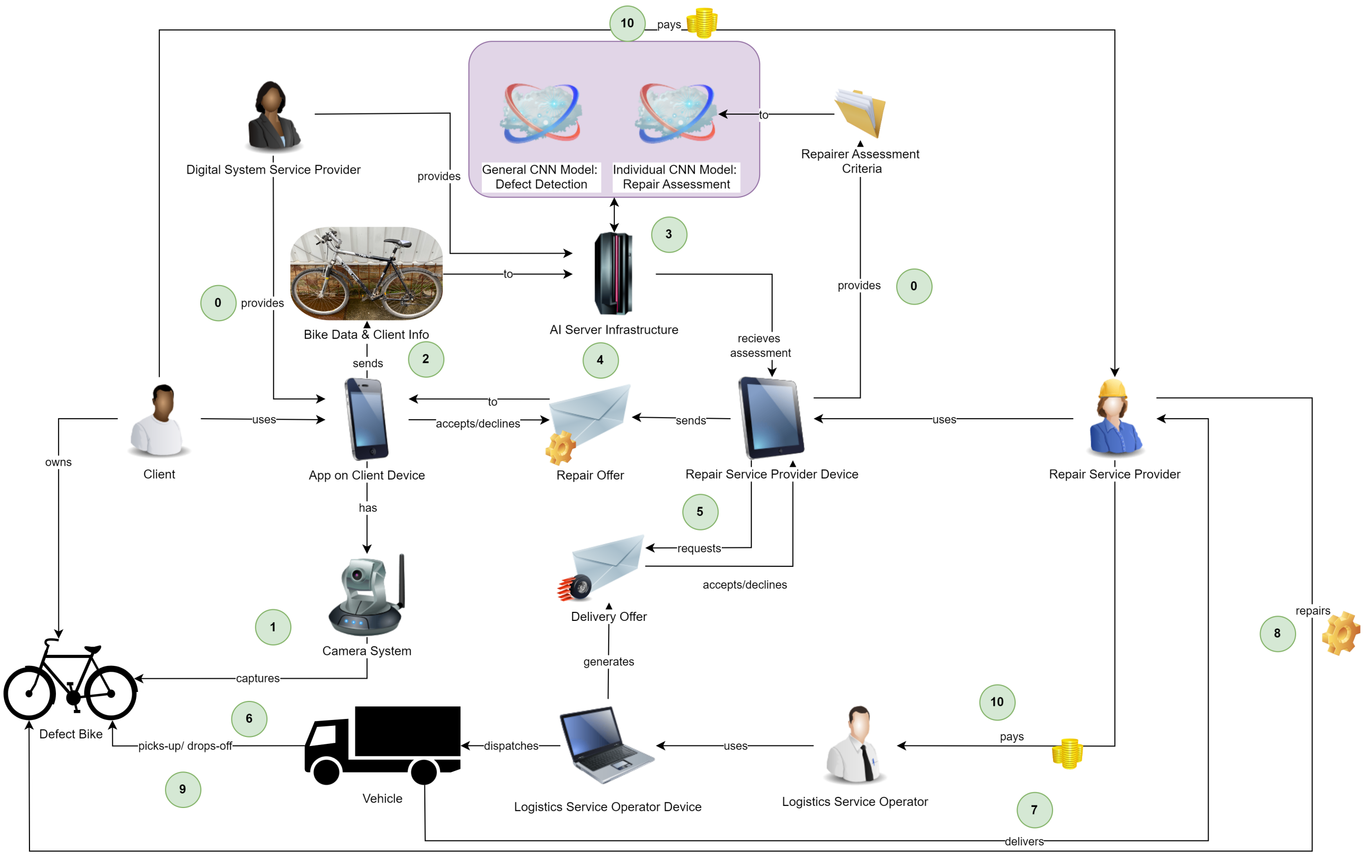

Figure 1. Product-Service-System for in-use bicycle repairing.

Criteria. The models are, therefore, analyzing the visible defect and missing parts on the bicycle and classifying the bicycle either as *reparable* or *not feasible for repair*, as described in Section IV.

The analysis of both the AI-based models is then transferred to the *Repair Service Provider*, who reviews the results and, if fitting for them, submits an offer to the *Client* (Step 4). If the client accepts the offer, the *Repair Service Provider* will contact the *Logistics Service Provider* to receive an offer for the transportation of the bicycle in the next step (Step 5).

By accepting the offer, the *Logistics Service Provider* will pick up the bicycle from the *Client* (Steps 6 and 7) to deliver it to the *Repair Service Provider*, who will fix and return it upon completion of the task (Step 8 and 9).

After the bicycle is delivered back to the *Client*, he pays the *Repair Service Provider*, who is paying on his terms the *Logistics Service Provider* for his logistics services.

IV. Scope of the AI-support

In order to address the requirements raised by the stakeholders, two distinct AI models are necessary to answer both the question about the repair worthiness of an item and the overall condition of its components. Those two models, although both based on CNNs, are different in their nature and how they are conceptualized in terms of data usage.

As described in Section I, the repairer needs essential information to determine if he is capable of repairing the bicycle and assessing the cost for repair on his side: *What is damaged?* and *Is it feasible for me to repair it?* We, therefore, handled those two information requirements as distinctive tasks, where we needed a specialized model for each of them. Hence, we designed two different labeling structures to enable the model to adapt to the two initial questions. For both models, a total number of 672 images were used for the training process, distributed in different labeling constellations.

The **General CNN Model: Defect Detection** is, therefore, responsible for identifying the different parts of a bicycle and their status in terms of damage or obsolescence of a given part. Its labeling structure is based on the PBS, as already introduced by the authors [2], in order to describe the composition setup of a bicycle and the functionalities of the different components. For this model, all the collected images of the different bicycles were classified and labeled according to the directly visible criteria. For example, in Figure 2, it is clearly visible that the chain that drives the shaft is broken. Also, the same applies to parts that are missing since they are for a given type of bicycle (e.g., mountain bicycle, trekking bicycle, etc.), not apparent. The model identifies, as a result, the type of component the bicycle is composed of as well as the general state of the same.

Figure 2. Bicycle from the data set without a functioning chain.

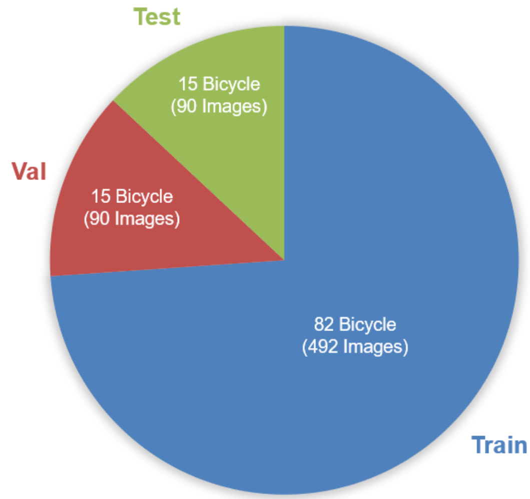

Figure 3. Bicycle-level stratified split of the dataset.

The **Individual CNN Model: Repairability Assessment** is in contrast to the further mentioned Model, much more relying on the context of the labeling since it evaluates the feasibility of the repairing process for a given repairer. The division in *reparable* and *not feasible for repair* is, therefore, subject to a multitude of different factors, including economic assessments and business model considerations, logistics management, and technical specialization and knowledge, as well as business-to-business contracts between repairers and certain manufacturers. The labeling process was conducted for this model in close collaboration with the repairer to reflect the decision a human repair operator would make by assessing the bicycle in front of them.

V. AI-based Methodology

This section elaborates on the AI-based methodology, including the experimental setup, preparation of training, validation, and test sets, and the AI-based architecture utilized with selected hyperparameters.

A. Preparation of training, validation, and test sets

The bicycle dataset consists of 115 distinct bicycles. However, a total of 112 bicycles, corresponding to 672 images, are considered for the experiments, excluding the children's bicycles. As outlined in Section II, each bicycle is captured from different angles and frames, resulting in multiple images belonging to each bicycle. The method makes the dataset more comprehensive, allowing for a more in-depth analysis of the bicycles' features and designs.

However, dividing the dataset at the image level could cause different frames of the same bicycles to appear in both the training and test sets. Consequently, when the model is tested on the unseen data, it may have already encountered the same bicycle from a different frame during the training phase, potentially compromising its ability to generalize effectively. Therefore, a bicycle-level stratified split is carried out as described in Figure 3.

As illustrated in Figure 3, 82 bicycles are utilized for training, with 15 bicycles allocated for optimizing the hyperparameters and another 15 for testing the final model performance. This structured approach enhances reliability and ensures robust evaluation.

B. AI-based Architecture and modeling process

The Constructed AI-based architecture utilizes the InceptionV3 network pre-trained on the ImageNet dataset [13]. The accessibility of pre-trained networks significantly facilitates the adaptation of CNNs in classification tasks, thereby diminishing the necessity for substantial computational resources and allowing for build-upon models trained on extensive datasets [7].

In addition, custom layers, including **GlobalAveragePooling (GAP), FCL, dropout**, followed by the **final FCL** for the target output classes, are added on the top of the pre-trained network as illustrated in Figure 4. Integrating custom layers on top of the pre-trained network can efficiently adapt the feature extraction capabilities to meet the requirements of the new tasks.

Subsequently, the model training is carried out utilizing the prepared training set and fine-tuned on the prepared validation set. The model is fine-tuned by freezing some of the pre-trained layers and allowing the remaining ones to train along with the custom layers. In addition, the process involves tuning several hyperparameters, including the selection of optimizer, learning rate, learning rate schedule, dropout rate, regularization rate, and batch size. Given that AI-based models are highly configurable through their hyperparameters, the fine-tuning of hyperparameters varies depending on the prediction task. Section IV already outlines the two distinct objectives this study addresses. Therefore, the considered hyperparameters, along with their fine-tuned values, are explicitly presented for the two prediction tasks in Subsection VI-A and VI-B.

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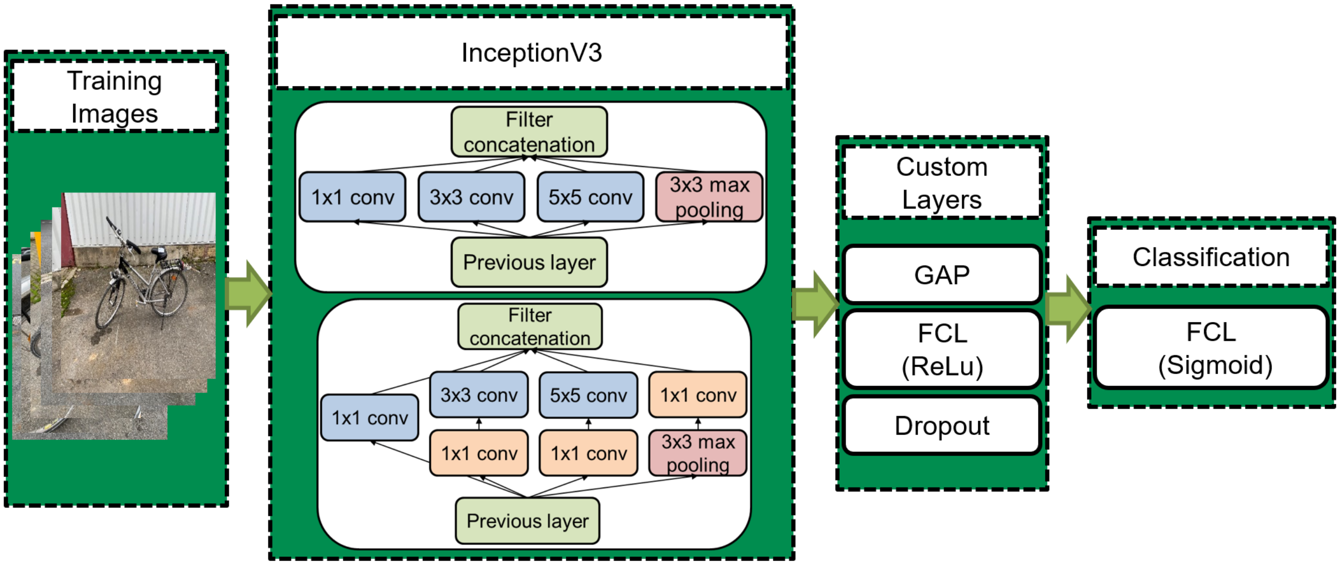

Figure 4. InceptionV3 architecture: Pre-trained on ImageNet dataset and fine-tuned with custom layers.

Moreover, early stopping is deployed to avoid overfitting and improve model generalization. Consequently, the training process is halted if the model performance does not improve on the validation set for 10 consecutive epochs. The early stopping technique is applied based on the monitoring of loss computed on the validation set. This technique allows the model to learn essential patterns without fitting the noise in the training data.

Most notably, the final classification for the bicycle for each use case is determined by counting the frequency of each predicted label across all images. As mentioned, each bicycle has multiple images captured from different angles and frames. The final classifier generates a prediction for each image after processing them independently.

Subsequently, these predictions are aggregated by deploying a majority voting mechanism. Consequently, the final class for the examined bicycle is determined by the prediction that receives the highest number of votes.

VI. Results and Analysis

This section demonstrates the final effectiveness of the constructed models for two distinct prediction tasks. The task of detecting defects and assessing the overall repairability of the bicycles on unseen test data.

The information about each bicycle component, as well as the overall assessment of the bicycle's repairability, is derived from the PBS developed in collaboration with the repair service provider, as outlined in Section II. Moreover, this section includes the performance metrics of the constructed classification models, as assessed through the classification report and the confusion matrix for each of the presented prediction tasks.

A. Defect Detection

In the context of the defect detection task, the bicycle chain is selected as the component to be examined. After deriving the respective information from the PBS, the model is trained and tested using the prepared sets outlined in Subsection V-A and the architecture presented in Subsection V-B. In addition, Table I describes the selected hyperparameters with the fine-tuned values for the respective task.

TABLE I. HYPERPARAMETERS WITH THE CORRESPONDING FINE-TUNED VALUE FOR THE DEFECT DETECTION TASK

Hyperparameters	Fine-tuned value
Optimizer	Adam
Learning rate	0.0002
Learning rate scheduler	0.1953
Dropout rate	0.5918
Regularization rate	0.0767
Batch size	8
Number of layers to freeze	127

The detailed evaluation of the model's predictive capabilities to examine the bicycle chain is described in Table II. Table II highlights the key performance metrics, including the precision, recall, F1-score, and accuracy.

TABLE II. CLASSIFICATION REPORT SUMMARIZING FINAL MODEL PERFORMANCE FOR DEFECT DETECTION

	Precision	Recall	F1-score	Support
Functional	0.62	1.00	0.77	5
Defect	1.00	0.70	0.82	10
accuracy			0.80	15
macro avg	0.81	0.85	0.80	15
weighted avg	0.88	0.80	0.81	15

Finally, the confusion matrix focuses on the instances of misclassification. The confusion matrix for the defect detection task on the test set is visualized in Figure 5.

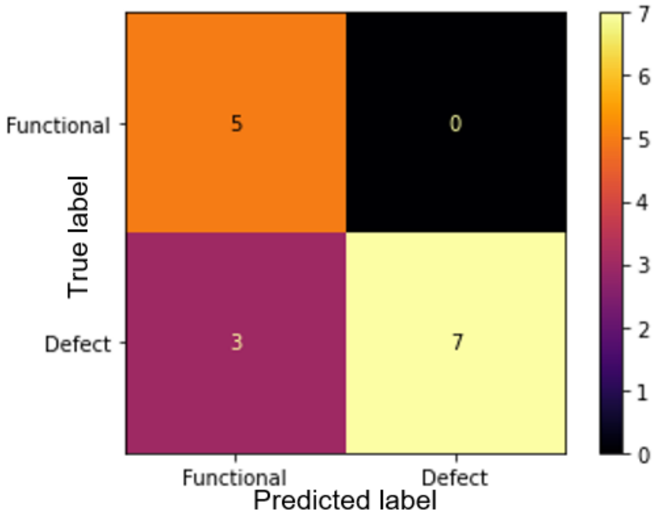

Figure 5. Confusion matrix representing the defect detection in the bicycle chain.

The results demonstrate a commendable performance, achieving a weighted average F1-score of 0.81 for 15 unseen bicycles. The model misclassified 3 of these bicycles, as indicated by the confusion matrix in Figure 5. Overall, the results suggest effective classification, considering the relatively small training set.

B. Repairability Assessment

The decision to assess repairability is subject to a multitude of different factors, including technical and economic assessments as well as business model considerations. The overall repairability assessment of the bicycle is carried out utilizing the same dataset split described in the Subsection V-A. In addition, the deployed model architecture is already presented in Subsection V-B but with different hyperparameters. Table III describes the considered hyperparameters and their corresponding fine-tuned values for the respective task.

TABLE III. HYPERPARAMETERS WITH THE CORRESPONDING FINE-TUNED VALUE FOR THE REPAIRABILITY ASSESSMENT TASK

Hyperparameters	Fine-tuned value
Optimizer	Adam
Learning rate	0.0005
Learning rate scheduler	0.2441
Dropout rate	0.4681
Regularization rate	0.0670
Batch size	8
Number of layers to freeze	84

Subsequently, the comprehensive performance analysis, including the precision, recall, which results in the F1-score, and accuracy of the repairability assessment classification model is presented in Table IV. The analysis indicates that the model attains a weighted average F1-score of 0.94 for 15 unseen bicycles, highlighting its capability to generalize effectively beyond the training set.

TABLE IV. CLASSIFICATION REPORT SUMMARIZING FINAL MODEL PERFORMANCE FOR REPAIRABILITY ASSESSMENT

	Precision	Recall	F1-score	Support
Repairable	0.86	1.00	0.92	6
Not Repairable	1.00	0.89	0.94	9
accuracy			0.93	15
macro avg	0.93	0.94	0.93	15
weighted avg	0.94	0.93	0.94	15

Finally, the confusion matrix provides a comprehensive assessment of the model's predictive performance, identifying specific instances of misclassification. The confusion matrix for the repairability assessment classification task is illustrated in Figure 6.

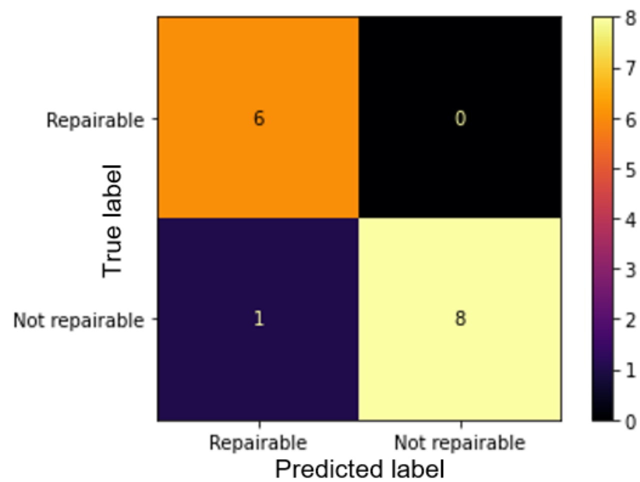

Figure 6. Confusion matrix representing the overall repairability assessment of the bicycle.

The confusion matrix demonstrates effective performance by the constructed model in distinguishing bicycles as repairable or not feasible to repair, with only one misclassification occurring among the 15 unseen bicycles in the test set.

VII. Challenges and Future Work

Although the application domain is outlined by the Product-service-system itself, there is still the necessity to deal with several challenges in that context. On the one hand, the proposed service system is, generally, still in its conception phase, and although it has been discussed with service partners in this domain, the overall applicability for maintaining repair services has still to be proven successful. The trained AI-based models, on the other hand, showed how AI-supported digital systems could leverage sustainable systems and enable a higher degree of knowledge generation at an earlier stage of the decision process.

Moreover, the presented classification results utilize the majority voting mechanism that efficiently considers the information provided from multiple viewpoints. In addition, the approach leverages the predictive outputs of a single classifier, based on the idea that variations in viewpoint can influence recognition performance. However, to better assess the robustness of the suggested approach, there are possible potential future directions. In addition to considering the information from multiple viewpoints, the proposed majority voting mechanism can be extended by taking the confidence scores assigned by the classifier to each image into account. Moreover, introducing a minimal confidence threshold may also contribute to reducing the influence of uncertain labels by ensuring that only predictions with a higher degree of confidence are included in the final vote.

Another possible future direction can be the extension of the proposed model functionality. So far, the defect detection model has only been trained to examine one specific component to prove the capabilities of the tuned hyperparameters. Therefore, it is necessary to examine in future research how the model would perform in the case of detecting multiple components. However, while it is possible to build a multi-output model to evaluate damages and thus guide repairability decisions, it encounters significant challenges. In general, finding the right balance between generalizability and specificity is essential as the models that are too specialized for one set of situations could not function effectively in a wider variety of situations. Therefore, it is essential to determine which particular output of the model will be examined on the validation set. This determination will help optimize the number of layers to freeze while utilizing a pre-trained model, as well as the selection of the optimizer with learning rate and the other hyperparameters.

Most notably, the model for repairability assessment, however, is, for now, trained on the requirements and specifications of one repair service provider. This means that for another repair service provider, a separate model needs to be trained if the specifications deviate from one another. Future research should, therefore, focus on how this system could be improved to reduce the expenditures for training and provide the framework to accommodate the diverse specifications of different repair service providers. Specifically, we propose a reconfigurable pipeline framework that facilitates the customization of training processes according to the specific requirements of each repair service provider. This flexibility would enable stakeholders of the system to select tailored training criteria, thereby ensuring that the resulting models are aligned with their unique operational contexts and respective needs. In addition, it is essential that the system incorporates functionality to dynamically switch between different models based on insights obtained from the training analysis and performance metrics. This dynamic adaptability would empower repair service providers to deploy the most suitable model in response to evolving conditions and particular challenges, thereby improving operational efficiency and advancing service quality across a spectrum of repair environments.

VIII. Conclusion

The paper presented a possible approach for an AI-supported repair ecosystem for bicycles, as well as two AI-based models optimized by hyperparameter tuning to detect damage and assess the overall feasibility of a given bicycle and its repair. The conceptualized ecosystem can be used in further research as a foundation to flesh out sustainable business models for repairing, remanufacturing, and refurbishing, and thus as a starting point for a demonstration of such systems in the scope of follow-up experiments. In addition, the reconfigurable pipeline framework that has been suggested for future development would make the system adaptable and customize the training process in alignment with the requirement of the repair service provider. As stated before, the system itself, as well as the AI-based components, still needed to be evaluated in their overall applicability for the Circular Economy Service domain to contribute to a broader application of smart and sustainable product services.

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