sustainability

Review

Toward Life Cycle Sustainability in Infrastructure: The Role of Automation and Robotics in PPP Projects

Madeleine Hoeft [1,*], Marianne Pieper [2], Kent Eriksson [3] and Hans-Joachim Bargstädt [2]

[1] Department of Real Estate and Construction Management, KTH Royal Institute of Technology, 11428 Stockholm, Sweden
[2] Faculty of Civil Engineering, Chair of Construction Engineering and Management, Bauhaus-Universität Weimar, 99423 Weimar, Germany; marianne.pieper@uni-weimar.de (M.P.); hans-joachim.bargstaedt@uni-weimar.de (H.-J.B.)
[3] Sustainable Finance Lab, Center for Construction Efficiency, Department of Real Estate and Construction Management, KTH Royal Institute of Technology, 11428 Stockholm, Sweden; kenteri@kth.se
* Correspondence: hoeft@kth.se

Abstract: This article identifies how project life cycle characteristics and automation and robotic technologies influence the sustainability of public-private partnership (PPP) infrastructure projects. The result of the article is a model of how public and private collaborations can leverage technology and project organization to make infrastructure more sustainable. Based on a comprehensive literature review, the model subdivides sustainability into engineering, project management, environmental, social, and economic dimensions. Engineering sustainability concerns the applicability of technologies to infrastructure PPP sustainability. The project management sustainability is decisive for ultimately creating environmental, social and economic sustainability within and beyond infrastructure PPP projects. The model identifies that the procurement phase is of particular importance for sustainable infrastructure PPPs. Successful sustainable infrastructure procurement likely includes such factors as increased transparency, participation, and stable, capable project alliances with a shared vision and clear goals. The model also identifies that, throughout the whole project life cycle, actions in the form of collaboration, experimentation and platformization promote sustainability. The findings in this article add to the understanding of how transformation toward increased sustainability can be achieved by individual organizations, their network, and ecosystems of public, private and civic actors.

Keywords: public-private partnership; sustainability; construction automation; robotics; BIM; life cycle; infrastructure

Citation: Hoeft, M.; Pieper, M.; Eriksson, K.; Bargstädt, H.-J. Toward Life Cycle Sustainability in Infrastructure: The Role of Automation and Robotics in PPP Projects. *Sustainability* **2021**, *13*, 3779. https://doi.org/10.3390/su13073779

Academic Editor: António Abreu

Received: 2 March 2021
Accepted: 25 March 2021
Published: 29 March 2021

1. Introduction

Public-private partnership (PPP) projects have gained worldwide popularity as an innovative method to deliver infrastructure, such as transport, water, waste, power, social and government infrastructure [1]. A public sector client initiates PPP projects with the key objective to procure public services at high quality in relation to the associated costs, and the PPP literature refers to this as Value for Money (VfM) over the project life cycle. In long-term collaborations with private actors, the planning, funding, construction and operation of public assets and services are bundled together to increase efficiency and bridge financial gaps [2]. As such, PPPs aim to improve project performances by using risk allocation mechanisms, knowledge and resources more efficiently.

However, due to their long-term nature and fragmented distribution of powers and responsibilities, PPP projects often show signs of broken agency, with stakeholders making decisions in their own, short-term interest, which ultimately puts the project success at risk and is a barrier to innovation and efficiency [3].

In parallel to the growing interest in PPP project structures, the use of construction automation and robotics (CAR) is being explored to improve productivity, stakeholder collaboration and high-risk working conditions, especially in mega projects [4]. While a clear definition is missing, CAR sees applications across the whole asset life cycle in both "design (e.g., using Computer Aided Design), construction (e.g., to control the use of machines onsite) and management (e.g., the use of Building Information Models (BIM))" of buildings and public infrastructure [5]. Technologies cover for instance "robotic control, sensing, vision, localization, mapping and planning modules", for quality control, educational purposes, risk management, and sustainability simulations of design alternatives. Despite rapid advancements in software and hardware development that have fueled this trend, implementations on a larger scale in construction and civil engineering projects are still rare [6]. Common barriers include the high initial investments for CAR solutions and their transformative impact on organizations and processes, as well as a lack of technological maturity and economic competition [5,7]. Next to that, factors like construction workplace safety, technological reliability and durability as well as the relations between project partners and equipment vendors also affect the implementation [8]. Nevertheless, with conventional building methods reaching their limits in today's industry, it is predicted that the adoption of automated construction techniques will see an S-shaped acceleration similar to the one of personal computers in the 1990s [9].

This outlook is especially relevant as the sustainability of infrastructure and construction projects becomes central to public debates and industry actions. The aspiration, to achieve a "state of the global system, including environmental, social and economic aspects, in which the needs of the present are met without compromising the ability of future generations to meet their own needs" [10] is often refined as a triple bottom line (TBL) perspective. Depending on the context, some research add further layers to the TBL perspective, e.g., technological or institutional sustainability [7]. It is recognized that resilient infrastructure is crucial to provide universal access to infrastructure services, such as clean water and sanitation, sustainable cities and communities, and affordable and clean energy. As a consequence, the United Nations (UN) see PPP projects as an important tool to achieve the Sustainable Development Goals (SDGs) [11]. In research, the focus is also shifting toward sustainability aspects of PPP projects as an emerging area in the literature [12]. Cheng, Wang et al. [2] discuss the concept of PPP 3.0 as a sustainability-oriented PPP form, involving the government, enterprises and the public in a development process that is evaluated using the TBL-perspectives instead of only economic metrics. The PPP 3.0 concept promotes a long-term perspective since it includes a whole-process assessment when evaluating project strategies. It is developed in a reaction to previous PPP project types, which lack attention to social and environmental impacts [2]. The social dimension is particularly commonly neglected, probably because social impacts are more difficult to quantify and measure than economic and environmental factors [13,14]. Moreover, despite advances in research, a comparative case study of European road PPP projects revealed difficulties to implement sustainable practices in real-life projects [15].

The field of CAR is also affected by the demand for sustainability, which will be a motivating factor for increasing adoption of CAR (e.g., for reducing waste). As guidance, Pan, Linner et al. [7] propose a framework to assess construction automation and robotics for buildings in a sustainability context. While inferences can be made, specific infrastructure aspects are however not covered in this framework. Love, Liu et al. [16] use BIM metrics for life cycle monitoring of PPP projects, yet solely from the perspective of economic sustainability. Moreover, the potential of BIM and Mix Reality in assisting "whole life design optimization, whole life costing, [and] integration of construction and maintenance of assets at the early stage" [12] (p. 10) is examined in a sustainable PPP context.

Overall, there is a lack of research on the integration of technological innovation into PPP structures [1]. Findings indicate a high potential to leverage sustainability across the life cycle of PPP projects through automation and robotics, but no approach has yet investigated the links between all three fields in a holistic way as visualized in Figure 1.

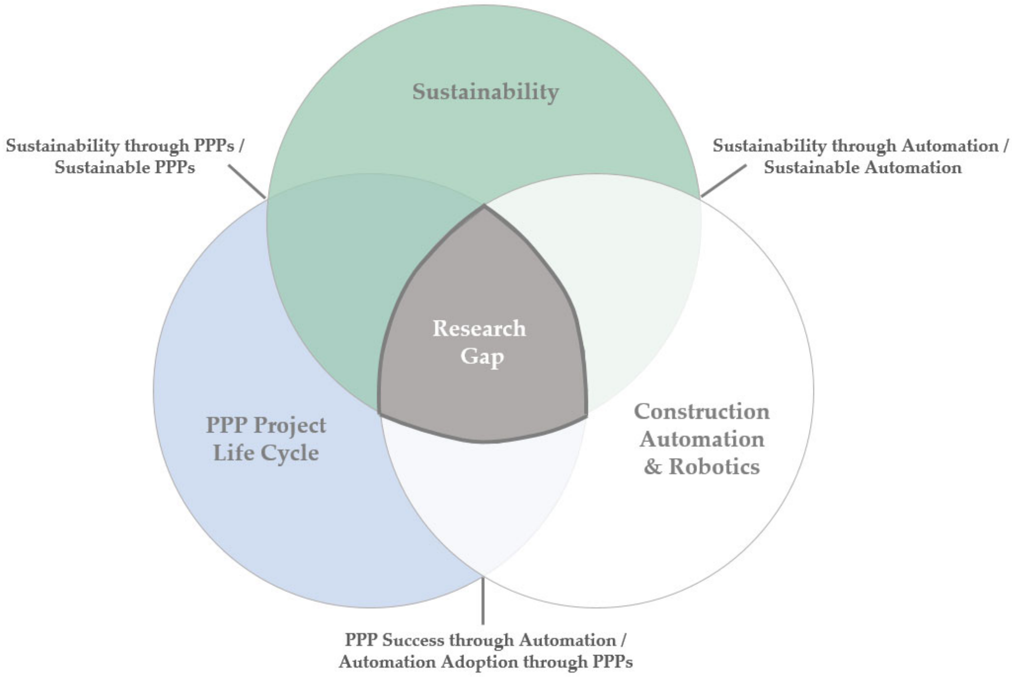

Figure 1. Research areas and overlaps.

While automation is widely expected to support sustainable developments, innovation in PPPs can have both positive and negative impacts, and should hence be assessed carefully and holistically across life cycle stages and stakeholder perspectives [17]. Liu [18] proposes to assess the "dynamics of technological transition toward sustainability" (p. 2) from a multi-level perspective, starting from clear definitions of the firm-level (i.e., individual stakeholders) through the project level (i.e., life cycle stages) as the "knowledge building blocks" (p. 2) to eventually unveil the more macro level ecosystem implications. For CAR to increase sustainability in PPP projects, an understanding of both the barriers and enablers of this transformation, and how PPP stakeholders can ensure sustainable adoption, is needed.

Therefore, three central research questions are addressed in this paper: (1) What are the major emerging research streams and key factors in PPP projects, CAR, and sustainability assessments? (2) How does CAR influence sustainability in the context of PPP projects? (3) What are the implications for stakeholders on a firm, project and ecosystem level?

2. Materials and Methods

A result of the described research gap is that it is necessary to create new knowledge by building on carefully selected sources of information. The design of this approach is therefore consistent with a conceptual paper, which is characterized by drawing on multiple concepts, literature streams, and theories [19]. Conceptual papers propose new relationships between constructs by developing logical connections between them, rather than testing them empirically [20]. A common research design for conceptual papers is the model approach, which is characterized by building a theoretical framework that explains and predicts the relationships between subject areas. For this purpose, new connections between subject areas are identified and it is explained how a sequence of events leads to a certain outcome [19]. The methodological framework to answer the research questions is visualized in Figure 2, followed by a detailed explanation of the steps.

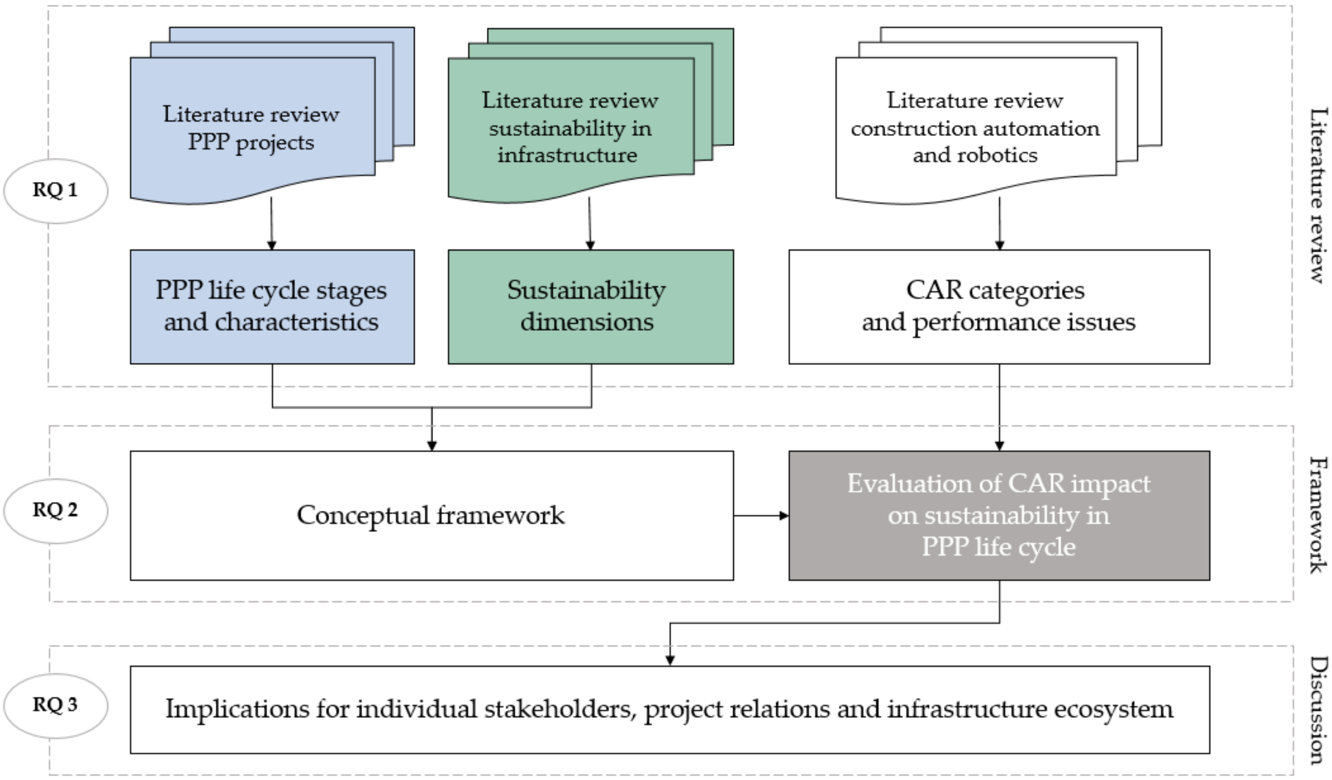

Figure 2. Research steps.

The literature review aims to identify relevant sustainability dimensions, PPP life cycle phases and key characteristics as well as CAR categories and performance issues with respect to the sustainability dimensions and PPP stages (Figure 2). All three topics show a broad scope of literature sources. Therefore, a semi-systematic literature review is conducted to answer research question 1. Semi-systematic literature reviews are used to provide an overview of a topic and its research development over time. It aims to present the developments and current state of knowledge in the three areas under review [21]. This type of analysis should be used to identify themes, theoretical perspectives, or common problems within the defined research disciplines [22]. Framework conditions for the literature to be selected were specified. To generate the appropriate literature sources that address the interrelationships of the three defined topics, search strings were generated. Figure 3 presents these conditions as well as the results of the paper selection process. Documents found with the defined search strings were evaluated according to the established rules. Unfitting articles (e.g., agriculture or aerospace technology) were ruled out based on title and abstract.

Subsequently, a modeling approach is adopted to address research question 2 (RQ2) based on the literature review. The key review findings are evaluated as opportunities (i.e., minimize risks or maximize rewards) and challenges (i.e., maximize risks or reduce rewards) arising from CAR adoption across life cycle stages and sustainability dimensions. The chosen approach allows revealing previously unexplored connections between these issues, without relying on empirical data [18,19]. Based on this elaboration, the impact of CAR on life cycle sustainability of PPP projects is evaluated to answer research question 3 (RQ 3). Finally, effects on the life cycle phases and individual stakeholders are discussed, before highlighting potentially larger ecosystem implications.

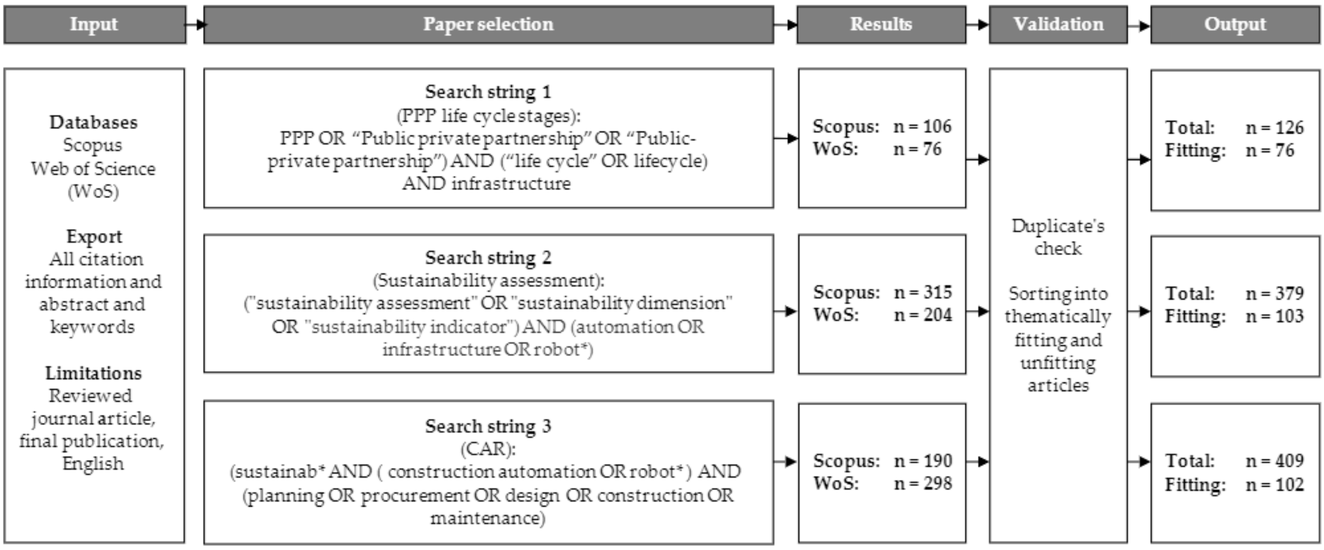

Figure 3. Literature search strings and results.

3. Results

3.1. Literature Review

3.1.1. PPP Project Life Cycle Stages

PPP projects are highly dynamic, complex endeavors, whose characteristics, challenges and stakeholder networks change frequently over the course of the project. Less than 5% of the stakeholders are involved in all stages, which bears the potential for shortsighted opportunistic behavior of the parties if coordination and integration of actors across phases is not carefully managed [23]. That requires effective interface management between organizations, phases and interdependent physical entities accompanied by phase-based evaluations and feedback loops throughout the life cycle [24]. PPP project outcomes are affected by three different institutional elements: regulative (e.g., legislation, auditing and dispute resolution rules), normative (e.g., standardized agreements, gateway review processes and VfM analyses) and cognitive structures (e.g., trust on private and public sector, transparency, fairness, accountability) [25]. However, while the first one is seen as a necessity that governs the procedures laid out by normative guidelines, it is the cognitive part that decides whether a true partnership is established in the long run, based on a shared vision implemented in a bottom-up manner. In an adequate set-up, PPPs then have the ability to reduce the holistic asset costs over the entire lifetime [26]. Not only does this result in superior project performances compared to other procurement strategies, it can also allow the stakeholders to tolerate temporary cost increases or reduced demand, for instance due to external shocks or changes in consumption patterns. Indeed, from a game theory perspective, PPP is considered the most adequate contractual form to provide incentives for the private sector to accelerate innovative and clean investments [27].

Planning

The public sponsor or client, often supported by third-party consultants, evaluates the suitability of PPP procurement and prepares a project conception for the following request for proposals (RFP). As part of the planning stage, pre-project studies are performed, a risk management is set up and project teams as well as the design of the PPP arrangement are structured [28]. This phase is characterized by informal institutional logic with few contractual arrangements and connects a myriad of stakeholders such as users, interested civic groups, regulators and NGOs. Due to the dynamic nature of networks, the actors may be inclined to push costs and risk considerations to later phases, which underlines the importance of sound governance structures from the start [23]. In contrast, a lack of comprehensive PPP regulations beyond guidelines and by-laws is likely to contribute to project struggles [26]. Additional failure factors include the use of outdated forecast methods which in return increase the demand error rate, poor transparency, differences in interests and expectations of the project parties and a lack of clearly defined objectives and stakeholder roles [29]. Throughout the whole planning and procurement, a close communication with end-users is beneficial to understand community needs and increase engagement, yet is often neglected in practice [23].

Procurement

Following the planning stage, the proposals submitted by private bidders are evaluated and negotiated. Due to the project scope, proposals are typically submitted by a group of private actors (e.g., asset developer, operator, financial institutions). While there is a lack of formal indicators to measure the process efficiency of tendering, bidding and contract negotiations [24], criteria for the bid evaluation itself commonly include financial, managerial, technical, safety and environmental parameters [30]. The procurement stage is highly complex and, if managed poorly, can have a negative impact on the competition among bidders and project outcome [30]. For instance, actors may not participate in the bidding process if they perceive the risk of losing as too high in relation to the associated cost of preparing the bid. Imbalanced risk allocation can also lead to inaccurate, expensive pricing or represent a barrier for smaller and/or less experienced actors. Soomro and Zhang [31] add that vague contract descriptions, a weak screening process and consequently the selection of an unsuitable concessionaire endanger the project's VfM. Therefore, an open and transparent process in line with international standards and a competitive market with technologically skilled actors is required [26]. Upon awarding of the contract to a winning consortium, a special purpose vehicle (SPV) is set up as the joint platform for public and private stakeholders to realize the project [32]. The PPP's capital structures and financing terms are also determined in this stage.

Design and Construction

In the PPP implementation phase, the private consortium takes over the leading role to design, construct and commission the asset, while the public sponsor loses centrality [23]. Strong coordination mechanisms must be in place to "achieve intrinsic motivation for all project team members, who traditionally might operate in a more fragmented and individualistic manner" [33] (p. 3). Many of the activities at this stage are related to contract management, including responsibility allocation, output monitoring, change management and dispute resolution [28]. Simultaneous design and construction activities in connection with poor supervision and regulation practices due to a lack of experience and bargaining power from the public instance often cause disputes [34]. As a result, the public sector is frequently pushed to accept massive financial compromises [35]. Liu, Love et al. [24] therefore emphasize the need for a phase-based evaluation, that does not only assess the final asset by cost and time metrics, but performs milestone-based checks with regard to, e.g., cost, time, quality, safety management, health conditions, material and resource utilization and the effectivity of conflict management strategies. With regard to technological innovation in design, the contract timing impacts the "ability to perform life cycle design innovation of different magnitudes" [33] (p. 10) depending on when the private actors get involved in the project.

Operation and Maintenance

The operation phase covers the longest period of a PPP project, connecting the public and private project actors with the asset's end-users. While often not considered part of a construction project, Alexander, Ackermann et al. [32] advocate for seeing the operation phase as an integral part of PPPs. This may be contrary to existing contractor business models focusing on the creation of the asset rather than its operation. However, neglecting the long-term view can trigger complex dynamics and organizational feedback loops in the event of late rework and risk events. Páez-Pérez and Sánchez-Silva [36] see a typical principal-agent problem, where the actors' goals do not coincide and information asymmetry prevails. After recovering the costs of the design and construction phase, the private SPV members lose interest in holding and maintaining the asset [23]. To ensure a high quality of the asset, the public entity must enforce effective service level agreements that define the remuneration and performance structures [32]. Potential approaches can be availability-based or revenue-based strategies. However, as external events out of the concessionaire's control can occur (e.g., earthquakes, demand changes related to market dynamics), it is difficult to link remuneration only to observable performance metrics. The public actor needs to perform inspections and determine the maintenance strategy's compliance to prevent shirking and opportunistic behavior [36].

If projects struggle during the operation phase, this commonly stems from poor transparency, inadequate feasibility studies where the actual demand differs from forecasts, or project objections by civil and public actors. Tariq and Zhang [34] extent this list of failure factors with poor public supervision practices, a failure to enforce end-user payments and poor system maintenance leading to interrupted services. In the context of social housing, housing finance limitations can act as a trigger for inaccessibility and in consequence a lot of unsold properties [37]. Huge political risks are borne by the private party due to frequent political changes throughout the operation period [29]. In addition, direct financing by end-users (e.g., through tolls in transport projects), comes with great uncertainty regarding costs and revenue. Next to ensuring adequate service provision, governments should therefore guarantee minimum usage or revenue coverage to minimize the risk premium demanded by private actors and prevent bankruptcy.

3.1.2. Sustainability Assessment

Sustainability aspects in the built environment cover "construction works, parts of works, processes or services related to their life cycle that can cause a change to the environment, to economic conditions or to society or quality of life" [10]. Considering all TBL framework dimensions throughout the life cycle of a project requires satisfying different groups of stakeholders with a variety of interests from planning through construction and maintenance. This makes sustainability evaluations very complex and at the same time underlines the importance to develop an appropriate sustainability assessment tool [38]. In addition to the established TBL approach, there are several articles highlighting other sustainability aspects such as technical, engineering and institutional sustainability [39–42]. Extending the assessment beyond the TBL categories thus appropriately reflects the integration of tools and technologies available to the industry, governmental policies and societal needs [39]. Li et al. [43] also state that comprehensive evaluation indicators are often missing or cannot be mapped to existing TBL dimensions. Consequently, they integrate engineering and project management sustainability for a holistic examination of PPP projects. The engineering perspective includes technical areas that require consideration due to the complexity of infrastructure projects [40]. Project management complements communication aspects, soft skills or human resources management as factors for successful project implementation [43].

Many papers define indicators for the sustainability assessment of infrastructure, which differ in the details of the indicators and their classifications as well as in the characteristics of the indicators due to the consideration of a specific project type (e.g., bridges, roads, schools) or construction type that entails certain specifications. Nevertheless, the definition of suitable indicators as one of the biggest challenges in sustainability assessment [44]. This paper makes reference to the sustainability dimensions and indicators of Li et al. [43] (Table 1). Their work examines PPP projects in urban water treatment, but many of the indicators are general [45,46] and therefore applicable to other infrastructure types.

Table 1. Sustainability dimensions based on Li et al. [43].

Dimension	Definition	Indicators (Examples)
Economic sustainability	"[. . .] long-term, stable, and reasonable investment returns to the project itself but also the impact on the local economy and development."	Life cycle cost Sustainable cash flow Fiscal pressures on government
Environmental sustainability	"[. . .] giving a better world to the future generation and protecting ecological balance and natural systems from destruction [...] to achieve energy conservation, emission reduction, and environmental protection."	Reduction of pollutant discharge Energy efficiency Protection for landscape & historical sites Use of innovation materials
Social sustainability	"[. . .] providing the public with satisfactory goods and services through measures that enhance the social development potential of the project area, provide employment opportunities for local people, and improve the quality of life."	Public satisfaction Impact on social development
Engineering sustainability	"[. . .] sustainable development of the project itself, specifically, its durability (i.e., engineering quality), operation, and maintenance capability and the sustainability of the technology itself."	Construction quality Control of pollution sources Adoption of advanced technology Sustainability of technology itself Operation & maintenance capabilities Use of construction waste
Project management sustainability	"[. . .] profitable, fair, transparent, safe, ethical, and environmentally friendly project delivery, which aims at a project deliverable that is socially and environmentally acceptable throughout its life cycle."	Organization structure Continual improvement of the operation management system Competence & skill of the project team

A general consideration is the dynamic nature of sustainability assessments fueled by evolving perceptions of sustainability over time due to parallel societal, political, economic, organizational and technological changes [47], which precludes the completeness and generality of a framework. Nevertheless, this indicator system provides guidance for systematic quantification and analysis of PPP project sustainability.

3.1.3. Automation and Robotics

Based on the literature collected, developments in automation and robotics related to infrastructure planning, procurement, construction and maintenance, can be structured in three main streams: (1) technologies related to design and project management along the life cycle, (2) off-site prefabrication of asset components and systems, and (3) on-site technologies for surveying, assembly tasks and condition monitoring.

Design and Project Management Technologies

Due to project complexity, the implementation of construction projects is often associated with delays and cost increases, which are contrary to the required and desired sustainable development of buildings and infrastructure [48]. Emerging technological trends such as AR and VR, sensing and monitoring or BIM contribute to the automation of design and project management processes and allow a reduction of human interventions in on- and off-site construction work [49,50]. The increasing diversity of technologies has placed the need for interoperability throughout the project life cycle at the core of many discussions. Interoperability requirements are a computerized life cycle workflow model, a detailed BIM with embedded building accessories as well as a rationalized generation of tasks for automated manufacturing systems [50]. Beyond visualizations, BIM enables simulations and performance analysis, mathematical optimization and process automation, both in early stage planning and during project execution. It is a virtual environment in which all stakeholders can be involved to test real conditions before implementation in order to improve the overall project success [51]. That allows a more transparent management of all stakeholders' interests [52].

With the help of automation, processes become streamlined, while information loss, errors and conflicts are minimized. A more standardized planning and design process enables objective quality control and gives architects or engineers more time for creative developments [53]. BIM can be used to improve material, component and concept decisions and weighs them against each other based on energy saving potential or cost impact before the construction work starts [54]. In addition, real-time visualization makes design implications more comprehensive to a greater number of stakeholders. Automated documentation enables a greater level of detail, agile, customized information extraction and saves paper waste [52,55]. Integrating all data into a single source increases the reliability of information. Existing data, such as material and quantities, can be further used to prepare tasks for automated manufacturing systems thus increasing productivity in execution as well [50].

Computerized feedback loops and control and decision points enable not only the assessment of quality at a certain point, but also predict the impact of the decision throughout the life cycle to enable sustainable decision making [56]. Linked to artificial intelligence, project management analyses beyond humans processing abilities can generate valuable decision-making insights in much shorter time, greater speed and higher accuracy. Better decisions in turn can lead to overall improvements in productivity, safety, quality, and scheduling [53]. During maintenance, digital twins of assets assist both in the automated collection and analysis of monitoring data and in the planning of redevelopment activities. For instance, large historic site preservation can be supported by a combination of BIM and other digital tools, e.g., photogrammetry or 3D scanning [57].

In order for these advantages to be fully realized, certain framework conditions and further technical developments are required. Modelling as well as the integration of technical tools often require manual corrections during the process which can affect the input data of the simulation, making it only semi-automatic and thus prone to errors [53]. The main problem remains interoperability in construction, not only in the connection of information systems, but also of business processes, culture and values, as well as the management of contractual issues. There are interoperability problems in design due to a lack of exchange standards as well as in the exchange of digital parameterized workflow models and a lack of optimized generation of tasks for automated manufacturing systems derived from a BIM. The diversity of software applications, on the other hand, creates confidence in data exchange and leads to the lower cost impact of inefficient interoperability [50]. Alongside these technological challenges, users need to be trained in the ability to use and beneficially apply digital methods or software which involves initial investments of time and cost [55]. This may lead to a threat of displacement and impairment of many people in the industry and their job security [49]. On the other hand, some fields are too complicated to be programmed and require heuristic knowledge and experience that only a trained engineer possesses [53]. While the need for a widespread adoption of data analytics in construction is recognized, a lack of qualified personnel and technology-averse practitioners are main barriers [49]. The application of automation and information technology requires a cultural shift in organizations, followed by a redesign of processes and employee roles so that technology can be fully integrated and used as a management platform in decision-making processes [52].

Off-Site Technologies

Off-site construction relocates work steps previously performed on-site to a more controllable indoor factory setting. Here, semi- and fully automated construction processes are integrated using intelligent machines and robotic systems. That has major implications not only for the project management structures, but also for the socio-technical arrangements in human–machine-interactions, the environmental impact of processes and materials, and the transparency and access to relevant information improve due to automated processes. At the same time, it needs training and support for personal development to navigate the changing circumstances as an employee. That includes the ability to influence and configure machine options, the organization of working times, reconsiderations of physical and psychological job requirements and employment security. Managed successfully, the transition to more off-site construction and less manual work can then enhance technical quality and reliability, process resilience and timeliness. Shorter production times also allow energy savings to reduce the environmental impact of the project [56].

Architects and engineers in early planning stages bear the responsibility to integrate advanced fabrication requirements into their design work [58]. Supported by parametric and computational design approaches, they can enable the aspired environmental, social and economic benefits in a smooth workflow. In contrast, without the required interoperability, the isolation of automated manufacturing systems turns into a bottleneck for collaborative environments and service-based manufacturing networks [50]. This is a particular barrier for the large share of small and medium-sized companies, as they often cannot bear the high-volume technological investments on their own and rely on shared investment schemes to introduce automated processes. The machinery needs to be flexible, both in on-site and off-site settings [59]. Nevertheless, even if the financial power is given, the multitude of human and digital interfaces comes with the risk of inefficiency, high costs and high error rates for geometrically optimized structures. This makes streamlined manufacturing processes a key priority and lever for cost savings [60]. Furthermore, the location dependency and in some cases inflexibility of automation systems is a major weakness due to high transportation costs, logistic constraints and transport emissions. This drives the need for future local production of prefabricated elements or modules, for instance through transportable and highly specialized machinery [59].

On-Site Technologies

Yang, Fu et al. [61] broadly group on-site applications of construction automation and robotics into full automation, semi-automation and teleoperation. Myung, Wang et al. [62] cluster robotic solutions into wheeled robots moving on horizontal surfaces, wall-climbing or crawling robots, snake-like robots, modular robots, aerial vehicles and underwater vehicles can perform tasks in hazardous areas and increase safety for workers. In addition, sensor or BIM data is often linked to this equipment. The analysis of massive amounts of data gathered in operation systems during construction and maintenance allows for a transition from "automated monitoring" to "intelligent monitoring" decision-making supported by artificial intelligence and data mining. For instance, a combination of aerial vehicles and BIM can enable data collections for measurements and representation models to support decision-making throughout the life cycle [63].

The use of robotics and sensors in the field is impactful for several reasons. Generally, the strengths in on-site tasks stems from their workload capacity, their accuracy in repetitive tasks and the flexible programming [64]. For instance, a combination of BIM and unmanned aerial vehicle (UAV) recordings can visualize potential landscape integration, orientation and composition of future facilities, and spatial impacts on conservation and biodiversity in the early design phase to facilitate construction feasibility studies [63]. Their high mobility and low costs make UAVs a suitable tool for seismic risk assessment, disaster response and flood monitoring [62]. Additional applications are construction progress tracking, surveying and mapping [65]. During construction, the use of small-scale robotics for on-site fabrication of concrete structures allows for a higher level of variation and differentiation without geometric simplification, standardization and repetition. The equipment with sensors and mounting on a mobile platform further increases the robot's ability to work in parallel or collaboratively with humans, other robots and traditional construction equipment. That simplifies the construction process in terms of schedule and budget impact while allowing greater product complexity and material efficiency [66]. In the operation phase, inspection results become more objective and higher efficiency in repetitive tasks is achieved [67].

Future opportunities in on-site automation and robotics arise through the promotion of smart buildings and cities as cyber-physical systems, intelligent life-term monitoring of infrastructure assets and new analytics maintenance insights to ensure sustainable decisions [61]. Nagarajan, Li et al. [68] investigate robotic maintenance of critical infrastructure systems like transmission lines to minimize likelihood and severity of power outages which otherwise come with severe financial and societal consequences. Results of their research also allowed for a 95% reduction in energy consumption and carbon dioxide emissions by replacing helicopters with suspended robots for inspecting transmission lines. The environmental sustainability of construction logistics and waste management can also benefit from robotic technologies, e.g., by using automated systems able to process on-site material and in that way automate the construction of entire utility structures, especially in places that are potentially dangerous or difficult to access [69].

On the other hand, on-site robotics and automation still face limitations, mostly related to implementation costs, inflexibility and technological immaturity [68]. This includes measurement accuracy, sensor miniaturization, cost barriers, support of wireless communication, sensor smartness, long-term powering and durability issues [62]. With the rise of cyber-physical systems, security and stability concerns are a major vulnerability of automated solutions [61]. Without preventive measures, they can cause critical infrastructure to break down. Next to that, the lack of supporting infrastructure such as ICT, especially in harsh environments or remote areas, is also a barrier to process automation and real-time monitoring [52]. All these factors make monitoring systems only apparently easy to use and manage, whilst hiding drawbacks like high purchase and maintenance costs, and significant financial commitment for data management and processing to turn raw data into usable information [57]. In the field of on-site construction technologies, such as 3D printing, attention must be paid to environmental aspects, logistics and safety. While construction waste is reduced, the material itself currently still contains a high proportion of cement with a low environmental rating [70]. In addition, Hack and Lauer [66] find that the constructive capacities are very sensitive to outdoor conditions and timing, and therefore difficult to control. They also point out that use of robotics changes construction logistics and material system design to account for the specific needs of the technology. Finally, industry concerns exist about replacement of existing labor force and the earthquake resilience of 3D-printed structures [71].

3.2. Evaluation Framework

Based on the literature review, a framework was derived that comprehensively summarizes the key sustainability opportunities and challenges of CAR across the PPP life cycle. All aspects in the framework built on the previously presented literature findings. As shown in Figure 4, the sustainability dimensions and PPP project stages define the structure based on which the CAR impacts are evaluated.

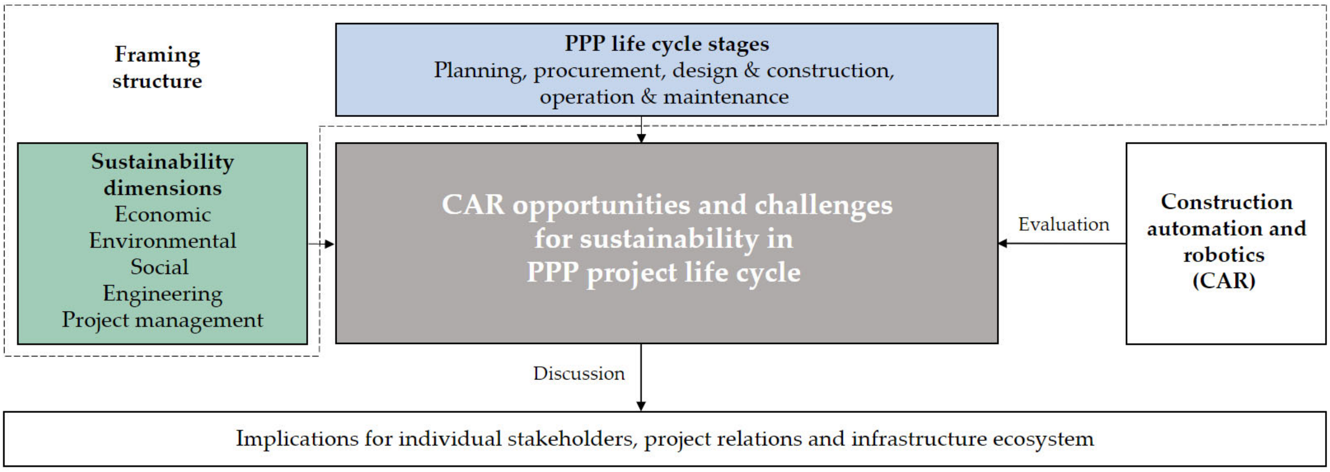

Figure 4. Evaluation framework.

Since the review and evaluation follow a purely qualitative approach, with the intention to link the main research streams in PPP, sustainability and CAR, no quantitative conclusions can be drawn in terms of severity and likelihood of their impact on each other. Nevertheless, Figure 5 clearly shows differences in the attention spent to certain PPP phases and sustainability dimensions with respect to new technologies.

Looking at the life cycle stages, much interest is paid to direct operational benefits and barriers of CAR, while impacts on the early phases of planning, project governance and procurement were often left unconsidered. For instance, no paper was identified throughout the review that discusses metrics to evaluate the social, environmental and technological potentials in the procurement stage. Instead, traditional cost and time metrics are commonly used when awarding the project contract to a consortium. In contrast, many different technologies and approaches are presented in the subsequent phases that aim at employing automation and robotics to increase sustainability. This underlines their significant transformative impact. Yet, while the importance is widely acknowledged, technological immaturity limits wide-spread project implementations for now. Regarding the vertical criteria of sustainability dimensions, the identified environmental aspects are mainly linked to positive implications across the life cycle, while the economic and social sustainability dimensions come with several risks and potential drawbacks. As the number of technologies increases and they become more mature, the generally positive impact is accompanied by several new challenges related to sustainability, that require close attention when discussing the integration of new technologies in PPP projects. This is underlined by the large number of engineering and project management sustainability aspects identified in the literature.

Sustainability dimensions	Evaluation	Evaluation of CAR opportunities and challenges based on sustainability dimensions	PPP life cycle stages: Planning	Procurement	Design & Construction	Operation & Maintenance
			Evaluation of CAR opportunities and challenges based on PPP life cycle stages			
Economic	Opportunties		**Life cycle cost** • Time savings and error minimization in feasibility studies **Sustainable cash flow** • Higher accuracy of long-term demand planning • Early anticipation of different risk scenarios • Lower cost for planning activities (e.g. surveying)	**Life cycle cost** • More reliable RfP documents for cost estimates • More objective bid evaluation	**Life cycle cost** • Data-driven LCC analyses and scenario modelling **Sustainable cash flow** • More reliable construction cost estimates • Data-driven performance tracking for risk management • Economies of scale due to on-/off-site standardization • Cost savings from on-site use of local materials	**Life cycle cost** • Need-based maintenance interventions • Reduction of costly equipment down-time **Sustainable cash flow** • Reduction of system failures (e.g. power outage) • Lower cost for seismic risk assessment, disaster response, and flood monitoring / assessment
	Challenges		**Fiscal pressure on government** • Significant financial commitment for data management	**Fiscal pressure on government** • Significant financial commitment for data management	**Sustainable cash flow** • High robotic equipment purchase and maintenance costs • Financial damage from cyber-physical system failures **Fiscal pressure on government** • Significant financial commitment for data management	**Sustainable cash flow** • High robotic equipment purchase and maintenance costs • Financial damage from cyber-physical system failures **Fiscal pressure on government** • Significant financial commitment for data management
Environmental	Opportunties		**Protection for landscape and historical sites** • Early evaluation of project landscape integration, orientation and composition • Remote wildlife studies to minimize disturbance and save biodiversity		**Reduction of pollutant discharge** • Transport emissions savings by on-site use of local materials **Energy efficiency** • Design optimized for energy usage (e.g. through LCA) • Energy savings in streamlined off-site construction **Use of innovative materials** • Use of new materials in 3D printing	**Reduction of pollutant discharge** • CO2 reduction by use of small, O&M robots **Energy efficiency** • Maintenance option evaluation (digital twin) • Need-based maintenance interventions (digital twin) • Energy consumption reduction by use of O&M robots **Protection for landscape and historical sites** • Non-intrusive renovation planning of heritage assets
	Challenges				**Use of innovative materials** • Environmental material characteristics limitations • Structural material characteristics limitations	
Social	Opportunties		**Public satisfaction** • More transparent communication of impacts through visualizations • Early evaluation of landscape integration, orientation and composition **Potential impact on social development** • Data-based selection of urban regeneration areas • Early evaluation of infrastructure impact on social disparities		**Public satisfaction** • More transparent public communication of impacts through visualizations • Design optimized for end-user well-being (e.g. healthcare, education)	**Public satisfaction** • Condition-based maintenance to ensure occupant safety with fault warnings • Improved end-user well-being (e.g. healthcare, education) **Potential impact on social development** • Reduction of catastrophic failures of critical infrastructure
	Challenges		**Potential impact on social development** • Changes in local and national job market structures and individual job securities • Potential biases in AI-based planning		**Potential impact on social development** • Changes in local and national job market structures and individual job securities	**Public satisfaction** • Improved end-user well-being (e.g. healthcare, education) **Potential impact on social development** • Potential biases in AI-based operations • Large-scale damage to critical infrastructure due to vulnerability of cyber-physical systems • Changes in local and national job market structures and individual job securities

(**a**)

Figure 5. *Cont*.

Sustainability dimensions	Evaluation	Mapping of CAR opportunities and challenges based on sustainability dimensions	PPP life cycle stages: Planning	Procurement	Design & Construction	Operation & Maintenance
			Evaluation of CAR opportunities and challenges based on PPP life cycle stages			
Engineering	Opportunties				**Sustainability of technology itself** • Increased lifespan of components and systems **Construction quality** • Higher quality through design for manufacturing • Higher quality through collision checks and simulations • Higher quality through off-site construction • Higher quality through on-site robotic work **Control of pollution sources** • Reduction of noise and emissions through off-site construction • Reduction of construction waste	**Sustainability of technology itself** • Increased lifespan of components and systems **Operation and maintenance capabilities** • High mobility in seismic risk assessment, disaster response, flood monitoring and assessment **Control of pollution sources** • Monitoring of emissions through sensors
Engineering	Challenges		**Adoption of advanced technology** • Need for supporting infrastructure (e.g. ICT)	**Adoption of advanced technology** • Isolated automated systems as bottlenecks for new engineering collaboration environments • Immaturity of technologies associated with high project risks	**Adoption of advanced technology** • Interoperability barriers between software solutions • Lack of information for automated manufacturing in BIM • Material characteristics limitations • Need for supporting infrastructure (e.g. ICT) and logistics **Sustainability of technology itself** • High technology production footprints (e.g. robotics) **Use of construction waste** • Reduction of material waste	**Adoption of advanced technology** • Interoperability barriers between software solutions • Need for supporting infrastructure (e.g. ICT) **Sustainability of technology itself** • High technology production footprints (e.g. robotics) **Operation and maintenance capabilities** • Large-scale damage to critical infrastructure due to vulnerability of cyber-physical systems
Project Management	Opportunties		**Continual improvement of the operation management system** • More accurate planning process • Higher process efficiency • Limited information loss (BIM-/GIS-based planning) • Increased trust and transparency • Comparison of concept options for choice optimization		**Continual improvement of the operation management system** • More accurate D&C planning and execution processes • Higher process efficiency • Limited information loss (BIM-/IoT-based D&C) • Increased trust and transparency • Reduction of repetitive design tasks • Comparison of concept options for choice optimization • Unlimited working hours for machines • Real-time tracking of construction progress for timely reactions and control over changes • Computational feedback loops and milestone checkpoints	**Continual improvement of the operation management system** • More accurate O&M planning processes by linking additional information and sensor data to model • Increased management flexibility and remote diagnostics • Higher process efficiency • Limited information loss (BIM-/IoT-based O&M) • Increased trust and transparency • Unlimited working hours for machines • Real-time tracking of construction progress for timely reactions and control over changes • Computational feedback loops
Project Management	Challenges		**Organization structure** • Disruptive impact on culture, processes and organization **Continual improvement of operation management system** • Lack of holistic automation process approach • Challenge to access and apply relevant information from previous projects to enable learning **Competence and skill of the project team** • Need for IT-related staff training and support • Need for domain knowledge to check AI plausibility • Change in physical and psychological job requirements	**Organization structure** • Significant impact on contract management and risk allocation **Competence and skill of the project team** • Need for companies with technology capabilities to participate in bidding procedure • Need for public staff technology capabilities to evaluate bid	**Organization structure** • Disruptive impact on culture, processes and organization **Continual improvement of the operation management system** • Lack of holistic automation process approach • Need to ensure workers' control capacity over machines in the form of being able to influence and configure options • Challenge to provide optimal information to all stakeholders to enable learning • Difficult to leverage big data over lifecycle **Competence and skill of the project team** • Need for IT-related staff training and support • Need for domain knowledge to check AI plausibility • Change in physical and psychological job requirements	**Organization structure** • Disruptive impact on culture, processes and organization **Continual improvement of the operation management system** • Lack of holistic automation process approach • Need to ensure workers' control capacity over machines in the form of being able to influence and configure options • Challenge to provide optimal information to all stakeholders to enable learning • Difficult to leverage big data over lifecycle **Competence and skill of the project team** • Need for IT-related staff training and support • Need for domain knowledge to check AI plausibility • Change in physical and psychological job requirements

(**b**)

Figure 5. (**a**). Evaluation of CAR opportunities and challenges. (**b**). Evaluation of CAR opportunities and challenges.

In terms of the impact characteristics, engineering sustainability aspects are mostly related to the maturity of individual technologies and the resulting challenges and potentials. Once mature enough for industry implementation, the success level of automation and robotics is linked a lot more to the long-term project management sustainability and its framing capabilities. This concerns aspects of governance, culture and risk management within organizations and across the project stakeholder network of public, private and civic actors. Ultimately, these prerequisites enable economic, environmental and social sustainability: as examples, individual actors can increase worker safety, improve material properties and tap on new business opportunities and revenue sources. Within projects, emissions in construction and maintenance can be reduced and schedule and budget objectives can be met without exposing employees or public to hazardous conditions or compromising on the asset quality. Even beyond single projects, TBL sustainability can be leveraged as the stable provision of critical infrastructure not only gives access to basic goods and services (e.g., water, electricity, education, ICT), but is crucial to enable sustainable innovation (e.g., research and development activities, business networks) in a variety of industries.

4. Discussion

Introducing automation and robotics to infrastructure projects inevitably links a traditional, fragmented industry to technological innovations evolving at exponential speed. The performed review and evaluation of construction technology challenges and opportunities unveil several transformative impacts for the economic, environmental, social, engineering and project management sustainability of PPP projects. That requires action from individual public and private stakeholders on three, interconnected levels: in the internal organization (firm level), in their relations over life cycle stages (project level), and in the context of infrastructure and innovation networks (ecosystem level). To increase positive sustainability impacts through the adoption of the discussed technologies in PPP projects, actors can address three main fields: collaboration (interaction to innovate), experimentation (structured trial-and-error process), and platformization (social and economic interactions via online platforms). Konietzko et al. [72] identified these pillars in a smart mobility project aiming for circular innovation. Due to their close connection to the characteristics of sustainable infrastructure projects, they were deemed appropriate to also guide the given agenda. Figure 6 visualizes the overall perspective.

As the number of stakeholders along these dimensions increases, the impact of technological change is likely to grow as well and should be considered accordingly. Consequently, the following discussion presents an agenda of key aspects for individual actors along the life cycle, before focusing on their interactions in a PPP project and beyond as part of infrastructure ecosystems.

4.1. Firm-Level Implications

For the individual actors along the PPP life cycle, the deployment of CAR technologies is typically a larger investment. Without considering the socio-technical component of technology adoption, costly acquisitions may be rejected by the workforce or lead to frictional losses.

Collaboration: Employees of private entities must be able to confidently apply and control new CAR solutions and methods to avoid psychological and physical strain in terms of safety, job security, and stress. Public entities on the other hand need to train their staff to procure services effectively with the help of digital tools and not compromise bargaining power in negotiations with specialized private parties. Actions related to internal collaboration include building trust among colleagues and management, a clear vision, customized training processes and the re-evaluation of traditional team structures. It should be communicated transparently how jobs are expected to change and employees should receive a fair remuneration linked to the benefits obtained through technology.

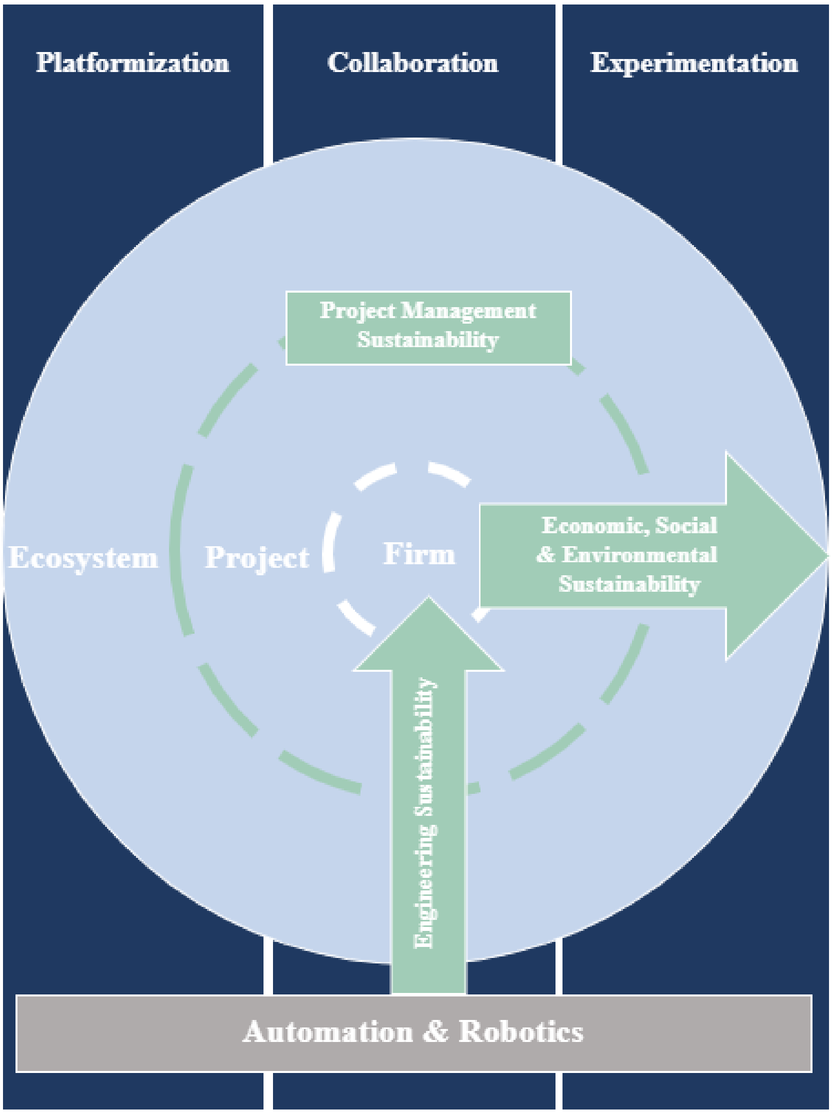

Figure 6. Impact of CAR on PPP sustainability.

Experimentation: In addition, the staff should be encouraged to use new technologies and act as internal ambassadors to promote their broader acceptance. This can include pilot tests of design and project management solutions such as BIM or regular internal showcasing of technologies. Collaborations with external start-ups can be executed, especially in areas where the company or public entity has limited innovation capabilities.

Platformization: It is important for both actors to encourage organizational learning and exchange within and across projects, for example by leveraging digital platforms. As data accumulates over time and can be analyzed with the help of AI, use cases and best practices for future projects can be identified, and productivity, time and cost savings are likely to be recognized. This in turn supports an increasing adoption of technology among the workforce. The resulting agility and flexibility make individual entities more resilient to inter-firm and ecosystem changes, build an innovative culture and reduce internal waste and costs. However, questions of key boundaries, access and control rights as well as the data management should be high on the management agenda.

4.2. Project-Level Implications

On an inter-firm level throughout the lifetime of a PPP project, the use of CAR can effectively address common factors for project failure such as a lack of transparency, inadequate feasibility studies, or poor manual infrastructure system maintenance. It also has profound impacts on the task allocations in the project execution, where new interaction between humans and machines as well as entire robotic systems change established job descriptions and assembly processes.

Collaboration: Setting the right stage already during planning and procurement is difficult and often neglected in terms of technology, yet crucial due to the complexity of PPP projects. Here, fair and transparent processes supported by technology can increase commitment and trust among project partners at an early stage. Bid participation should be actively encouraged, especially given that the common risk of insufficient competition, and thus a weak negotiation position for the public parties, is likely to increase with higher technological demands that especially small and medium enterprises (SMEs) cannot fulfill due to financial constraints. One way to address this barrier can be the compensation of losing bidders to partially offset the risk of preparing extensive bid documentation for those actors and make the participation attractive [25]. In addition, financing schemes negotiated during project procurement must also take the technological potentials and risks into consideration. That can imply the structuring of joint technology investments and the connection of financing terms to life cycle assessment parameters beyond the design and construction phase.

Especially for infrastructure assets that are subject to rapid changes like information and communication technology (ICT) infrastructure, it must be attractive for private actors to contribute to stable long-term services and technological updates of the assets as new innovations emerge. That creates the potential for new business models within the consortia, where, for instance, the main contractor and suppliers receive a share of the remuneration in a performance-based contract beyond the construction phase [73]. In addition, traditional procurement evaluation metrics must be reevaluated and extended to account for new risks emerging from the use of advanced construction automation and robotics. That concerns both risks linked to the technological immaturity and speed of change as well as cultural and political changes that may prove to be significant barriers to the project's agility and long-term predictability. In this regard, the selection of adequate evaluation metrics largely depends on the type of infrastructure and the project's goals concerning automation priorities and the aspired results. While the described impacts certainly require a clear project governance structure implemented by the public client through regulative and normative elements [25], specific attention must be paid to the cognitive institutional factors such as trust in the project stakeholders, transparency, fairness and accountability.

Experimentation: Defining minimum viable local pilot areas within a project, for example, where robotics are tested before a large roll-out is one way to guide technology adoption. Here, flexibility and agility come from a focus on clearly defined functionality rather than precise technologies to use in early project phases. The subsequent adoption of CAR for large project areas, for instance for off-site construction or 3D-printing, can then create scaling effects that not only increase quality and time, but can also decrease manufacturing costs. This is especially important recalling the need for availability and affordability of the asset for the end-user, for instance in large social housing schemes in developing countries.

Platformization: The main lever to realize sustainability impact through automation and robotics along the asset life cycle comes from an integrated project management workflow based on BIM, that considers off-site manufacturing requirements and robotic assembly processes at an early stage and links the different parties to overcome purely sequential work. In addition, the use of AI together with clear requirement guidelines from the individual parties are imperative to remove prevailing interoperability issues. However, while AI reduces the risk for human errors across the life cycle, new biases may be introduced through the design of algorithms and underlying data structures [74]. In PPP projects, this can for example refer to restricted access to critical infrastructure for certain population groups (e.g., social housing allocation schemes and microcredit provisions, access to transport systems, and water or energy supply management). Therefore, financial and human resources must be allocated to manage the generated data throughout the project, turn it into insightful information, and prevent external cyberattacks as well as biased learning models. Links to experimentation can be made in terms of test runs to measure the impacts of algorithms before they are being implemented on a large scale, especially during long-term infrastructure operations.

4.3. Ecosystem Implications

Beyond single projects, the adoption of automation and robotic technologies has implications for infrastructure ecosystems related to provision and use of assets and services.

Collaboration: Cross-project collaboration and inter-organizational learning, especially with respect to the use of new technologies, can help to offset high initial investment costs and prevent repetitive struggles. In addition, looking beyond the requirements of a single project and driving developments simultaneously ensures that supportive infrastructure (transportation, electricity, ICT) is in place for the use of CAR technologies in a PPP project. Moreover, the integration of civil parties and communities should be focused. Despite being the main users of infrastructure assets and services, they are often neglected in decision-making processes due to their informal links to PPP projects. In the light of rapid technological changes and political uncertainties, trust in the regulatory and institutional bodies is becoming increasingly important and may turn out to be decisive for the success or failure of sustainable technology implementation. This calls for transparency and clear communication of development plans to align civil, public and private interests and prevent riots and blockages.

Experimentation: Technological innovation on an ecosystem level can be promoted by a higher degree of interaction between academic, private and public institution for the establishment of research and development activities and test cases for new technologies before their adoption in large-scale PPP projects. Supported by public and private funding, prototypes can be developed and tested in a local "minimum viable ecosystem" [72] (p. 8) without the direct link to a single project. However, it is important to get early commitment and feedback from real projects to guide research activities toward the relevant directions. Iterative testing in cross-industry networks not only increases the public trust in new technologies, it also supports faster adoption of suitable solutions, reducing the risk of their obsolescence after long-term laboratory-based research activities. Not only the construction and operation of infrastructure assets see technology adoption, but also the vehicles (as for transport projects) and users interacting with it. For example, future roads need to cater to more electric cars and, in the longer run, autonomous vehicles [75]. While developments emerge from different industries, these systems need to be able to interact with each other to ensure safety and resource efficiency and allow for adjusted pricing mechanisms for the use of infrastructure services. Moreover, the possibility to present lighthouse projects and existing barriers encourages innovative future contributions.

Platformization: From a technical perspective, a rich digital replica of existing infrastructure assets created from the integration of BIM and geo information system (GIS) data in connection with, e.g., imagery data from UAV technologies can serve as an underlying basis for infrastructure planning and operations. For instance, data from this digital twin can be accessed by public parties when initiating new projects, reducing the need for extensive surveying and iterative evaluations in the longer run. From an economic point of view, platformization can be a way to share resources, especially heavy equipment across projects. It also opens up new possibilities for more flexible project structures, where a variety of actors can contribute to innovative infrastructure operations in a modular way. This, however, requires clear data standards, cybersecurity policies and governance structures established by the platform owners. Platformization and standardization on an ecosystem level can be driven by large industry actors or by public institutions. Ideally, it is characterized by close collaboration between both sides, not only to create transparency and engagement incentives for stakeholders, but also to provide a regulatory framework to ensure that the dominance of one party's interests does not harm the greater good of society and the environment.

5. Conclusions

This article aimed to analyze how the use of CAR in PPP projects can promote the transformation toward sustainable practices in public infrastructure. In particular, technologies for design and project management, off-site and on-site construction works are examined across the life cycle stages of PPP projects. After reviewing main research streams in these three areas, an evaluation framework is proposed. Lastly, ways to leverage the sustainability through experimentation, collaboration and platformization are suggested.

PPP project structures are a dynamic network of public and private stakeholders that engage in the delivery and operation of large infrastructure assets. This context is likely to act as amplifier of both positive and negative consequences of technological innovation. Required actions on both firm, project and ecosystem levels need to focus on providing settings to increase the engineering sustainability of technologies as well as the project management sustainability that provide the basis for successful CAR integration. Only with these prerequisites can environmental, social and economic sustainability be increased in and beyond individual PPP projects. As technologies evolve at a rapid speed, they not only mature more quickly and can overcome existing limitations, but they also have much shorter product life cycles that challenge established organizational and financing structures. Organizational agility and flexibility are therefore of high importance on a firm, project and ecosystem level. This includes a stakeholder mindset to learn and adapt iteratively, and open platforms that allow for modularized integrations of technological solutions. Given the ambivalent impact of CAR technologies on sustainability in PPP projects, it is not a panacea for today's inefficiencies whose use should be increased at all cost. Instead, it is seen as a means to increase sustainability given suitable and favorable context settings as discussed.

The findings of the authors have implications for several actors, both in infrastructure projects and for researchers and companies in construction automation and robotics. For PPP projects, it will support contractors, investors and municipalities in their decision-making processes toward sustainable project deliveries supported by automation and robotics. It provides financiers and insurers with an overview of the impact of automation on PPP risks and opportunities, as well as sustainability parameters. The review also indicates focus areas for actors in legislation to reflect on when aiming to establish legal frameworks for this field of innovation. From the technology point of view, it will help developers and researchers to improve their understanding of the business implications of their solutions and provide guidance on how to address market needs.

It should be noted that many of the publications reviewed focus on the contexts of China, the United States of America, and Australia, while for instance European and African perspectives are represented to a lesser extent. This is particularly important, because political circumstances and institutional maturity play a major role for the success of PPP projects and may hence affect to what extent technologies are implemented in infrastructure. Due to the review character of the paper and the discussion of emerging technologies that have only recently or not yet been implemented in real-life projects, limitations also include the lack of practical case validations. In addition, by adopting a high-level perspective, factors of individual projects or technologies are not taken into account.

6. Research Agenda

Future work should aim to foster a positive impact of CAR use on SDGs through the efficient use of technology applications. As pointed out previously in Figure 6, this concerns both the evaluation of different sustainability dimensions and strategies to introduce platformization, experimentation and collaboration principles into the infrastructure life cycle. Research activities could therefore address the following areas and questions (Table 2):

Table 2. Potential research areas and questions.

Research Area	Research Question
Economic, environmental and social sustainability	What are drivers of infrastructure projects to promote the SDGs and how can CAR technologies leverage them? What do concrete actions and best practices on an organizational, project and ecosystem level look like? How are technological solutions and PPP governance structures addressing the evolving, dynamic nature inherent to the understanding of sustainability?
Engineering sustainability	How can CAR use case scenarios in PPP projects be prioritized? What are metrics to evaluate the maturity and risks of technological solutions?
Project management sustainability	How can CAR be aligned with project management processes, knowledge management and organizational structures? How can PPP project governance and risk management be designed to account for technology-related risks? How can assessment and selection of project consortia be done in a transparent procurement process, and include metrics beyond purely economic indicators? What attracts innovative, potentially smaller actors to participate in PPP biddings?
Collaboration	What are best practices and strategies for multi-disciplinary and cross-industry collaboration around infrastructure automation? Which role do political circumstances and systems play in realizing sustainability benefits through infrastructure technology?
Experimentation	How can testbeds and minimum viable ecosystems be designed to reduce residual technology risks in actual infrastructure projects? Which incentives exist for public and private actors to engage in experimentation activities?
Platformization	How can marketplaces and transactions between stakeholders and projects be structured efficiently to lower the costs of acquiring and maintaining CAR equipment? What are the implications for stakeholder relations, e.g., in terms of platform access and big data management? How can the state, agencies and other government actors facilitate innovative PPP markets that integrate technology, infrastructure and sustainability?

The future research agenda will benefit from using various methods of both qualitative and quantitative nature to contribute to a holistic view. This can include case studies, interviews, observational research and analyses of quantitative data from the use of technologies during the asset lifecycle. Combining different data sources in 'big data' analysis can be used to develop ways to more dynamic measurements throughout the life cycle, for both social, environmental and economic sustainability. Performance measurements and comparative studies of best practices are assumed to further provide insights to practitioners across the world. Multi-disciplinary research designs are of high importance given the diversity of civil, public and private stakeholders linked to infrastructure projects and as well as the transformative impact of automation and robotics. As infrastructure assets themselves become smarter (e.g., smart roads, smart cities) in order to achieve sustainability goals and respond to changing demographic needs, design requirements and life cycle management strategies are likely to evolve as well. This may challenge both CAR technologies and infrastructure procurement approaches and should be considered increasingly in future research and public discourse.

Author Contributions: Conceptualization, M.H. and K.E.; methodology, resources, validation, formal analysis, writing, visualization, M.H. and M.P.; supervision, K.E. and H.-J.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received funding from VINNOVA, the Swedish innovation agency.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ma, L.; Li, J.; Jin, R.; Ke, Y.; Yuan, J. A holistic review of public-private partnership literature published between 2008 and 2018. *Adv. Civ. Eng.* **2019**, *2019*. [CrossRef]
2. Cheng, Z.; Wang, H.; Xiong, W.; Zhu, D.; Cheng, L. Public–private partnership as a driver of sustainable development: Toward a conceptual framework of sustainability-oriented PPP. *Environ. Dev. Sustain.* **2020**. [CrossRef]
3. Casady, C.B.; Eriksson, K.; Levitt, R.E.; Scott, W.R. (Re)defining public-private partnerships (PPPs) in the new public governance (NPG) paradigm: An institutional maturity perspective. *Public Manag. Rev.* **2020**, *22*, 161–183. [CrossRef]
4. Kim, T.; Lee, D.; Lim, H.; Lee, U.; Cho, H.; Cho, K. Exploring research trends and network characteristics in construction automation and robotics based on keyword network analysis. *J. Asian Archit. Build. Eng.* **2020**. [CrossRef]
5. Chen, Q.; de Soto, B.G.; Adey, B.T. Construction automation: Research areas, industry concerns and suggestions for advancement. *Autom. Constr.* **2018**, *94*, 22–38. [CrossRef]
6. Kim, M.J.; Chi, H.L.; Wang, X.; Ding, L. Automation and Robotics in Construction and Civil Engineering. *J. Intell. Robot. Syst. Theory Appl.* **2015**, *79*, 347–350. [CrossRef]
7. Pan, M.; Linner, T.; Pan, W.; Cheng, H.; Bock, T. A framework of indicators for assessing construction automation and robotics in the sustainability context. *J. Clean. Prod.* **2018**, *182*, 82–95. [CrossRef]
8. Sepasgozar, S.M.E.; Davis, S.R.; Li, H.; Luo, X.R. Modeling the Implementation Process for New Construction Technologies: Thematic Analysis Based on Australian and US Practices. *J. Manag. Eng.* **2018**, *34*, 12. [CrossRef]
9. Bock, T. The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. *Autom. Constr.* **2015**, *59*, 113–121. [CrossRef]
10. *ISO 15392:2019 Sustainability in Buildings and Civil Engineering Works - General Principles*; International Organization for Standardization: Geneva, Switzerland, 2019.
11. Cui, C.; Liu, Y.; Hope, A.; Wang, J. Review of studies on the public–private partnerships (PPP) for infrastructure projects. *Int. J. Proj. Manag.* **2018**, *36*, 773–794. [CrossRef]
12. Wang, N.; Ma, M. Public–private partnership as a tool for sustainable development—What literatures say? *Sustain. Dev.* **2020**. [CrossRef]
13. Hueskes, M.; Verhoest, K.; Block, T. Governing public–private partnerships for sustainability: An analysis of procurement and governance practices of PPP infrastructure projects. *Int. J. Proj. Manag.* **2017**, *35*, 1184–1195. [CrossRef]
14. Yuan, J.; Zhang, L.; Tan, Y.; Skibniewski, M.J. Evaluating the regional social sustainability contribution of public-private partnerships in China: The development of an indicator system. *Sustain. Dev.* **2020**, *28*, 259–278. [CrossRef]
15. Villalba-Romero, F.; Liyanage, C.; Roumboutsos, A. Sustainable PPPs: A comparative approach for road infrastructure. *Case Stud. Transp. Policy* **2015**, *3*, 243–250. [CrossRef]
16. Love, P.E.D.; Liu, J.; Matthews, J.; Sing, C.P.; Smith, J. Future proofing PPPs: Life-cycle performance measurement and Building Information Modelling. *Autom. Constr.* **2015**, *56*, 26–35. [CrossRef]
17. Lember, V.; Petersen, O.H.; Scherrer, W.; Ågren, R. Understanding the relationship between infrastructure public-Private partnerships and innovation. *Ann. Public Coop. Econ.* **2019**, *90*, 371–391. [CrossRef]
18. Liu, Z.; Stephens, V. Exploring innovation ecosystem from the perspective of sustainability: Towards a conceptual framework. *J. Open Innov. Technol. Mark. Complex.* **2019**, *5*, 48. [CrossRef]
19. Jaakkola, E. Designing conceptual articles: Four approaches. *AMS Rev.* **2020**, *10*, 18–26. [CrossRef]
20. Gilson, L.L.; Goldberg, C.B. Editors' Comment. *Group Organ. Manag.* **2015**, *40*, 127–130. [CrossRef]
21. Snyder, H. Literature review as a research methodology: An overview and guidelines. *J. Bus. Res.* **2019**, *104*, 333–339. [CrossRef]
22. Ward, V.; House, A.; Hamer, S. Developing a framework for transferring knowledge into action: A thematic analysis of the literature. *J. Health Serv. Res. Policy* **2009**, *14*, 156–164. [CrossRef] [PubMed]
23. South, A.; Eriksson, K.; Levitt, R. How Infrastructure Public–Private Partnership Projects Change Over Project Development Phases. *Proj. Manag. J.* **2018**, *49*, 62–80. [CrossRef]
24. Liu, J.; Love, P.E.D.; Davis, P.R.; Smith, J.; Regan, M. Conceptual framework for the performance measurement of public-private partnerships. *J. Infrastruct. Syst.* **2015**, *21*. [CrossRef]
25. Devkar, G.; Palliyaguru, R.; Oyegoke, A.S. The effects of institutional frameworks on implementation of PPP projects: A comparative perspective in Australia and India. *Int. J. Constr. Manag.* **2020**, *20*, 720–736. [CrossRef]
26. Bao, F.; Martek, I.; Chen, C.; Chan, A.P.C.; Yu, Y. Lifecycle performance measurement of public-private partnerships: A case study in China's water sector. *Int. J. Strateg. Prop. Manag.* **2018**, *22*, 516–531. [CrossRef]
27. Buso, M.; Stenger, A. Public-private partnerships as a policy response to climate change. *Energy Policy* **2018**, *119*, 487–494. [CrossRef]
28. Liu, J.; Love, P.E.D.; Smith, J.; Regan, M.; Davis, P.R. Life cycle critical success factors for public-private partnership infrastructure projects. *J. Manag. Eng.* **2015**, *31*. [CrossRef]
29. Zou, P.X.W.; Wang, S.; Fang, D. A life-cycle risk management framework for PPP infrastructure projects. *J. Financ. Manag. Prop. Constr.* **2008**, *13*, 123–142. [CrossRef]
30. Simon, L.; Jefferies, M.; Davis, P.; Newaz, M.T. Developing a theoretical success factor framework for the tendering phase of social infrastructure PPPs. *Int. J. Constr. Manag.* **2020**, *20*, 613–627. [CrossRef]

31. Soomro, M.A.; Zhang, X. Evaluation of the Functions of Public Sector Partners in Transportation Public-Private Partnerships Failures. *J. Manag. Eng.* **2016**, *32*. [CrossRef]
32. Alexander, J.; Ackermann, F.; Love, P.E.D. Taking a Holistic Exploration of the Project Life Cycle in Public–Private Partnerships. *Proj. Manag. J.* **2019**, *50*, 673–685. [CrossRef]
33. Antillon, E.I.; Molenaar, K.R.; Javernick-Will, A. Evaluating the Effect of Contract Timing on Lifecycle-Design Innovation in Public-Private Partnerships: Comparative Case Study of Highway Projects. *J. Constr. Eng. Manag.* **2017**, *143*. [CrossRef]
34. Tariq, S.; Zhang, X. Critical Failure Drivers in International Water PPP Projects. *J. Infrastruct. Syst.* **2020**, *26*. [CrossRef]
35. Bao, F.Y.; Chan, A.P.C.; Chen, C.; Darko, A. Review of Public-Private Partnership Literature from a Project Lifecycle Perspective. *J. Infrastruct. Syst.* **2018**, *24*. [CrossRef]
36. Páez-Pérez, D.; Sánchez-Silva, M. A dynamic principal-agent framework for modeling the performance of infrastructure. *Eur. J. Oper. Res.* **2016**, *254*, 576–594. [CrossRef]
37. Trangkanont, S.; Charoenngam, C. Critical failure factors of public-private partnership low-cost housing program in Thailand. *Eng. Constr. Archit. Manag.* **2014**, *21*, 421. [CrossRef]
38. Hasheminasab, H.; Gholipour, Y.; Kharrazi, M.; Streimikiene, D.; Hashemkhani, S. A dynamic sustainability framework for petroleum refinery projects with a life cycle attitude. *Sustain. Dev.* **2020**, *28*, 1033–1048. [CrossRef]
39. Boz, M.A.; El-Adaway, I.H. Creating a holistic systems framework for sustainability assessment of civil infrastructure projects. *J. Constr. Eng. Manag.* **2015**, *141*. [CrossRef]
40. Gharehbaghi, K.; McManus, K.; Hurst, N.; Robson, K.; Myers, M. Complexities in mega rail transportation projects: "Sydney metro" and "Melbourne metro rail" insight. *J. Eng. Des. Technol.* **2020**, *18*, 973–990. [CrossRef]
41. Spoann, V.; Fujiwara, T.; Seng, B.; Lay, C.; Yim, M. Assessment of public-private partnership in municipal solid waste management in Phnom Penh, Cambodia. *Sustainability* **2019**, *11*, 1228. [CrossRef]
42. Singh, R.K.; Murty, H.R.; Gupta, S.K.; Dikshit, A.K. An overview of sustainability assessment methodologies. *Ecol. Indic.* **2009**, *9*, 189–212. [CrossRef]
43. Li, H.; Xia, Q.; Wen, S.; Wang, L.; Lv, L. Identifying Factors Affecting the Sustainability of Water Environment Treatment Public-Private Partnership Projects. *Adv. Civ. Eng.* **2019**, *2019*, 7234. [CrossRef]
44. Ferrarez, R.P.F.; Vargas, R.V.; Alvarenga, J.C.; Chinelli, C.K.; Costa, M.A.; Oliveira, B.L.; Haddad, A.N.; Soares, C.A.P. Sustainability indicators to assess infrastructure projects: Sector disclosure to interlock with the global reporting initiative. *Eng. J.* **2020**, *24*, 43–61. [CrossRef]
45. Navarro, I.J.; Yepes, V.; Martí, J.V. A Review of Multicriteria Assessment Techniques Applied to Sustainable Infrastructure Design. *Adv. Civ. Eng.* **2019**, *2019*. [CrossRef]
46. Aboushady, A.M.; El-Sawy, S.A.R. Qualitative assessment framework to evaluate sustainability indicators affecting infrastructure construction projects in developing countries using the analytical hierarchy process (AHP). *Wit Trans. Ecol. Environ.* **2013**, *179*, 1309–1320. [CrossRef]
47. Hallin, A.; Karrbom-Gustavsson, T.; Dobers, P. Transition towards and of sustainability—Understanding sustainability as performative. *Bus. Strategy Environ.* **2021**, 10.1002/bse.2726. [CrossRef]
48. Raouf, A.M.I.; Al-Ghamdi, S.G. Building information modelling and green buildings: Challenges and opportunities. *Archit. Eng. Des. Manag.* **2019**, *15*, 1–28. [CrossRef]
49. Mansouri, S.; Castronovo, F.; Akhavian, R. Analysis of the Synergistic Effect of Data Analytics and Technology Trends in the AEC/FM Industry. *J. Constr. Eng. Manag.* **2020**, *146*. [CrossRef]
50. Tibaut, A.; Rebolj, D.; Nekrep Perc, M. Interoperability requirements for automated manufacturing systems in construction. *J. Intell. Manuf.* **2016**, *27*, 251–262. [CrossRef]
51. Sanhudo, L.P.N.; Martins, J. Building information modelling for an automated building sustainability assessment. *Civ. Eng. Environ. Syst.* **2018**, *35*, 99–116. [CrossRef]
52. Paiva, G.; Agra, R.; de Tomi, G. Application challenges for information and automation technologies in an underground mine in Brazil. *Rev. Esc. De Minas* **2017**, *70*, 93–97. [CrossRef]
53. Khairulzaman, H.A.; Usman, F. Automation in civil engineering design in assessing building energy efficiency. *Int. J. Eng. Technol.* **2018**, *7*, 722–727. [CrossRef]
54. Starynina, J.; Ustinovichius, L. A multi-criteria decision-making synthesis method to determine the most effective option for modernising a public building. *Technol. Econ. Dev. Econ.* **2020**, *26*, 1237–1262. [CrossRef]
55. Ismail, N.A.A.; Idris, N.H.; Ramli, H.; Sahamir, S.R.; Rooshdi, R.R.R.M. Sustainable BIM-based cost estimating for quantity surveyors. *Chem. Eng. Trans.* **2018**, *63*, 235–240. [CrossRef]
56. Zhang, L.; Balangé, L.; Braun, K.; Di Bari, R.; Horn, R.; Hos, D.; Kropp, C.; Leistner, P.; Schwieger, V. Quality as driver for sustainable construction-Holistic quality model and assessment. *Sustainability* **2020**, *12*, 7874. [CrossRef]
57. Rea, P.; Pelliccio, A.; Ottaviano, E.; Saccucci, M. The Heritage Management and Preservation Using the Mechatronic Survey. *Int. J. Arch. Herit.* **2017**, *11*, 1121–1132. [CrossRef]
58. Yang, X.; Loh, P.; Leggett, D. Robotic variable fabric formwork. *J. Comput. Des. Eng.* **2019**, *6*, 404–413. [CrossRef]
59. Wagner, H.J.; Alvarez, M.; Kyjanek, O.; Bhiri, Z.; Buck, M.; Menges, A. Flexible and transportable robotic timber construction platform-TIM. *Autom. Constr.* **2020**, *120*, 17. [CrossRef]

60. Kromoser, B.; Ritt, M.; Spitzer, A.; Stangl, R.; Idam, F. Design concept for a greened timber truss bridge in city area. *Sustainability* **2020**, *12*, 3218. [CrossRef]
61. Yang, L.; Fu, C.; Li, Y.; Su, L. Survey and study on intelligent monitoring and health management for large civil structure. *Int. J. Intell. Robot.* **2019**, *3*, 239–254. [CrossRef]
62. Myung, H.; Wang, Y.; Kang, S.C.J.; Chen, X.Q. Survey on robotics and automation technologies for civil infrastructure. *Smart. Struct. Syst.* **2014**, *13*, 891–899. [CrossRef]
63. Rizo-Maestre, C.; González-Avilés, Á.; Galiano-Garrigós, A.; Andújar-Montoya, M.D.; Puchol-García, J.A. UAV + BIM: Incorporation of photogrammetric techniques in architectural projects with building information modeling versus classical work processes. *Remote Sens.* **2020**, *12*, 2329. [CrossRef]
64. Rivera, R.G.; Alvarado, R.G.; Martínez-Rocamora, A.; Cheein, F.A. A comprehensive performance evaluation of different mobile manipulators used as displaceable 3D printers of building elements for the construction industry. *Sustainability* **2020**, *12*, 4378. [CrossRef]
65. Ayman, R.; Alwan, Z.; McIntyre, L. BIM for sustainable project delivery: Review paper and future development areas. *Archit. Sci. Rev.* **2020**, *63*, 15–33. [CrossRef]
66. Hack, N.; Lauer, W.V. Mesh-mould: Robotically fabricated spatial meshes as reinforced concrete formwork. *Archit. Des.* **2014**, *84*, 44–53. [CrossRef]
67. Rea, P.; Ottaviano, E. Design and development of an Inspection Robotic System for indoor applications. *Robot. Comput. Integr. Manuf.* **2018**, *49*, 143–151. [CrossRef]
68. Nagarajan, B.; Li, Y.; Sun, Z.Y.; Qin, R.W. A routing algorithm for inspecting grid transmission system using suspended robot: Enhancing cost-effective and energy efficient infrastructure maintenance. *J. Clean. Prod.* **2019**, *219*, 622–638. [CrossRef]
69. Mascaro, R.; Wermelinger, M.; Hutter, M.; Chli, M. Towards automating construction tasks: Large-scale object mapping, segmentation, and manipulation. *J. Field Robot.* **2020**, *16*. [CrossRef]
70. Nisar, N.; Bhat, J.A. Effect of Rice Husk Ash on the Carbonation Depth of Concrete under Different Curing Ages and Humidity Levels. *J. Mater. Civ. Eng.* **2021**, *33*. [CrossRef]
71. García-Alvarado, R.; Martínez, A.; González, L.; Auat, F. Projections of 3D-printed construction in Chile. *Rev. Ing. Constr.* **2020**, *35*, 60–72. [CrossRef]
72. Konietzko, J.; Bocken, N.; Hultink, E.J. Circular ecosystem innovation: An initial set of principles. *J. Clean. Prod.* **2020**, *253*. [CrossRef]
73. Azcárate-Aguerre, J.F.; Den Heijer, A.; Klein, T. Integrated faades as a Product-Service System -Business process innovation to accelerate integral product implementation. *J. Facade Des. Eng.* **2018**, *6*, 41–56. [CrossRef]
74. Truby, J. Governing Artificial Intelligence to benefit the UN Sustainable Development Goals. *Sustain. Dev.* **2020**, *28*, 946–959. [CrossRef]
75. Saeed, T.U.; Alabi, B.N.T.S.m.a.; Labi, S. Preparing Road Infrastructure to Accommodate Connected and Automated Vehicles: System-Level Perspective. *J. Infrastruct. Syst.* **2021**, *27*. [CrossRef]