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Utilising Artificial Intelligence in Construction Site Waste Reduction

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Abstract: The purpose of this study is to examine how artificial intelligence (AI) can help reduce waste on construction sites. An explorative, mixed-method research design is deployed. Qualitative methods were utilised, including an extensive literature search, 32 interviews, a project visit, and participation in chosen seminars. Additionally, quantitative methods included an analysis of waste quantities in 161 construction projects, selected based on criteria for availability of data, as well as a targeted questionnaire with 21 respondents. Several methods were employed as means of triangulation, to increase the validity and reliability of the data in a complex and rapidly developing field. The study uncovers several possibilities and concludes with 18 proposed measures for waste reduction on a construction site, along with a set of recommendations for practical implementation. The recommended measures include defining appropriate targets for waste production, optimising resources, tracking continuously, reporting and presenting waste quantities, training, conducting inspections, and implementing specific routines for warehousing. The study helps bridge the gap between ambition and practice by highlighting considerations related to the practical implementation of measures for waste management and providing an understanding of which AI-based tools and measures are considered effective for waste reduction in construction projects.

Keywords: artificial intelligence, construction projects, sustainability, waste, waste reduction.

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1. Introduction

The ever-growing construction industry is accountable for nearly 40% of worldwide energy consumption and energy-related gas emissions (Global Alliance for Buildings and Construction, 2017), while the need for more sustainable solutions is growing just as swiftly. Implementing circular thinking and optimal waste management will be among the most important courses of action to fulfil national and international ambitions to reduce emissions (Avfall Norge, 2016; Olerud, 2019). A significant potential to increase productivity and sustainability is widely assumed to lie in the utilisation of new technology, digitalisation, and artificial intelligence (AI) (Becqué et al., 2016; Moen, 2017; Mejlænder-Larsen, 2019).

Construction waste can be defined as 'a material or product which needs to be transported elsewhere from the construction site or used on the site itself other than the intended specific purpose of the project' (Skoyles and Skoyles, 1987 as cited in Osmani, 2011). Reduction of waste on construction sites plays an important role in the usage and development of more sustainable solutions, and in the ongoing development of a sustainable industry; therefore, waste reduction is an important means to reach the 13th sustainability goal related to climate action (United Nations, 2021). Studies show that certain waste fractions have very high waste percentages (Hjellnes Consult, 2015; SSB, 2019), meaning that large amounts of such materials pass through the value chain without adding any practical value to a project. Existing literature identifies wood, plaster, cardboard and paper, plastics, and mixed waste as problematic waste fractions (Rønningen, 2000; Kartam et al., 2004; Osmani, 2012). However, a recent development with practical implications for sustainability is the increased use of AI in the industry, as data become more available and data processing capacity grows more affordable.

The purpose of this study was to examine how AI can help reduce waste on construction sites. An unambiguous definition of AI is currently lacking, especially in a construction context. Adio-Moses and Asaolu (2016) describes AI-based tools as tools capable of 'reasoning, planning, learning, natural language processing (communication), perception, and the ability to move and manipulate objects.

Three research questions are answered through a mixed-methods research design, providing quantitative data collected from the contractor and qualitative considerations from other parts of the value chain. Specifically, the study answers the following research questions:

- RQ1: Which measures are suitable for waste reduction on the construction site?
- RQ2: How can the identified measures be implemented?
- RQ3: How can AI contribute to the implementation of the measures?

The remainder of this article is organised as follows. The next section explains the review methodology. The results section presents findings from all described methods. These findings are further assessed, discussed, and summarised in 18 specific measures for utilising AI to improve waste reduction. The final section provides the conclusion, along with the implications of the study and avenues for future research. The conclusion also answers the research questions as defined, summarises the conducted research, and reflects upon the possibilities the study provides for future research, as well as the current study's limitations.

2. Method

To answer the research questions, the explorative research design combines quantitative and qualitative methods; methodological triangulation contributes to the inherent quality of the findings of the study (Love et al., 2002). Table 1 illustrates the research design, with its five phases of data collection and analysis. Each methodological technique is described and elaborated.

Initial research comprised a thorough literature search on the topic of waste reduction and the use of AI in the construction industry. In parallel, a document analysis of available material was conducted, to ensure the relevance of theoretical findings. Other qualitative methods utilised were semi-structured in-depth interviews, structured interviews, a project visit, a tour of the Norsk Gjenvinning plant, as well as participation in chosen seminars and webinars. Quantitative methods utilised include an analysis of data on waste disposal in 161 construction projects and a questionnaire distributed among the personnel responsible for waste management of ongoing projects in Skanska Norway. Further research was carried out by analysis and compilation of the collected data.

Criteria such as validity, reliability, and generalisability can indicate the quality of a study (Tjora, 2017). Validity is related to the relevance of the study itself, as well as the relevance of collected data; reliability is related to verifiability (Denzin, 2012). The literature search included an assessment of the relevance of the sources themselves in addition to the collected data. Similarly, in interviews, the relevance of both the interviewees and the questions themselves was assessed. Generalisability could be restricted, as the quantitative aspects of the study are based on projects from one contractor, and on new construction projects specifically; the results are not necessarily transferable to other actors or projects. However, reduced generalisability can be compensated for via a comparative research approach.

Table 1. The five phases of data collection and analysis.

	Phase 1: Framing the problem	Phase 2: Mapping of waste, causes, and effects	Phase 3: Mapping of techniques based on AI	Phase 4: Triangulation of data	Phase 5: Validation
Performed activity	Definition of purpose and aim; conceptualisation of problem statement in the context of the field	Identification of problematic waste fractions, activities, and processes	Identification of available techniques based on AI	Assessment of findings and the intersection between the two areas	Validation and refinement
Methodological technique	Review of previous research through literature search; document analysis; introductory conversations with relevant personnel	Mapping and evaluation of waste in 161 construction projects; questionnaire; targeted interviews; project visit; participation in chosen seminars	Mapping literature and lessons learned in pilots and case studies; targeted interviews; participation in chosen webinars	Combining evidence from the previous investigations, theoretical and practical findings; targeted interviews	Consulting informants, peer academics, and practitioners
Analysis	Assessment of early findings	Problematic waste fractions identified in quantitative analysis; cross-checked with existing literature and informants, summarised; causes of waste and effects of waste reduction mapped	Estimation of available technology and techniques enabling potential measures for waste reduction; mapping was done with the help of informants	Iterative assessment of findings in Phase 2 and 3; discussions with selected informants	Discussions with selected informants, peer academics, and practitioners; presentation of findings
Contribution to paper	Section 1 Section 2	Section 3 Section 4 RQ1 RQ2	Section 3 Section 4 RQ3	Section 4 Section 5 Section 6	All sections

For this study, this entailed using multiple methods and involving actors from various parts of the value chain in interviews and reviews throughout the process, as well as a validation of results in the final research phase.

The literature search was conducted to obtain insights into current and previous studies on waste reduction in the construction industry, as well as AI in the construction industry. The search commenced by selecting databases considered appropriate for finding studies on waste reduction and AI in the construction industry. The Scopus and Oria databases were chosen, due to their coverage of engineering-based publications. Search strings such as [waste AND (reduction OR minimisation) AND construction AND (project* OR industry)] as well as [artificial intelligence OR machine learning AND construction AND (project* OR industry)] were used to identify relevant literature. To ensure the provision of a state-of-the-art view of the topics, publications from 2000 or later were examined. Suggestions given by interviewees were also reviewed

Over the course of a year, 18 semi-structured in-depth interviews were conducted in person and via computer; in addition, 14 structured interviews were conducted in written form. The interviewees were actors from every stage of the construction project supply chain. Selection of the interviewees was based on inclusivity of different roles and perspectives throughout a project and its value chain, as well as suggestions from previous interviewees, building a strategic selection according to the recommendations of Dalland (2012). Interviewees included personnel with experience from waste management and general interest in environmental initiatives, as well as those with experience in the use of AI both within and outside the construction industry. The semi-structured approach facilitates a set structure for the conversation but provides paths for input from the informants themselves (Johannessen et al., 2016).

Where informants were unable to participate in the in-depth interviews, or for various reasons preferred another format, an additional 14 structured interviews were conducted in a written format. Challenges associated with this approach include fewer reflections from the interviewees and the increased possibility of misunderstanding; this was accounted for largely by asking follow-up questions. An overview of the background and contributions of the interviewees is summarised in Table 2. The total of certain characteristics may be greater than 18 or 14, respectively, as some informants fell into two or more of the defined categories.

The interviews followed one of two interview guides, developed after the initial literature search and document analysis. The first guide was structured to gather perspectives on problematic waste fractions, the origin of the identified fractions, suggested solutions, and challenges related to the reduction of the identified fractions. The second guide was structured to gather perspectives on the role of AI in waste reduction on construction sites. The interviews were recorded, transcribed, and categorised for further analysis. Thaagard (2013) suggests that the researcher strives to find a selection of interviewees that meets a theoretical saturation point, beyond which adding a new informant would no longer add anything significantly new to the research. Saturation was identified in this study by continuously assessing and comparing responses from the conducted interviews. Certain topics reached saturation point earlier than others; in these cases, an emphasis was placed on the unsaturated topics in any follow-up questions and further choices of interviewees.

Table 2. Interviewees.

	Semi-structured interviews		Structured interviews	
Characteristics	N	%	N	%
Total	18	100.0%	14	100.0%
Current title				
Architect	2	11.1%	3	21.4%
Client	0	0.0%	3	21.4%
Project manager	4	22.2%	1	14.3%
Project engineer	3	16.7%	3	21.4%
	2			
Purchasing	2	11.1%	0	0.0%
Skilled worker	1	11.1%	0	0.0%
Supplier	4	0.06%	2	14.3%
Researcher		22.2%	2	14.3%
Current field of work				
Academic	4	22.2%	2	14.3%
Practitioner	14	77.8%	12	85.7%
Previous experience				
Construction	10	55.6%	8	57.1%
AI	4	22.2%	6	42.9%
Both	4	22.2%	0	0.0%
Other	2	11.1%	0	0.0%

Additional observations were made during a project visit, a tour of the Norsk Gjenvinning plant, and participation in chosen seminars and webinars on the topic of waste reduction and/or AI. These further observations provided an additional understanding of the topic and contributed to the continuous validation of the results.

An analysis of the waste disposal in 161 construction projects was conducted to identify any problematic waste fractions, with respect to total volume, environmental impact or impact on project progress, management, or activities. The analysis utilised the tool *Grønt Ansvar* from Norsk Gjenvinning to provide an overview of disposed waste in terms of volume, weight, degree of sorting, and cost associated with waste management in selected projects (Norsk Gjenvinning, c. 2018). The waste reports are dynamic, and the system can single out selected fractions, amounts, costs, or projects on demand. The projects were deemed relevant for inclusion using the following criteria: used Norsk Gjenvinning for waste disposal through the entire production phase; did not use any other providers for waste disposal; and sufficient availability of further documentation, in case of any follow-up questions for the project or its team members. After this assessment, all projects meeting the criteria were included, as a bigger sample would make the data foundation more representative. For the analysis, the waste fractions were classified and categorised according to the guidelines provided by Norsk Gjenvinning. In addition, a distribution analysis was conducted according to Holme and Solvang (1996), to assess both total waste amounts, and amounts for each of the registered fractions. The biggest fractions were selected for further assessment.

The questionnaire distributed among those responsible for waste management and disposal in construction projects confirmed the findings from the waste-disposal analysis.

The questionnaire contained 25 questions in total, of which 15 were considered open, and 10 closed. The questions were tested before the final distribution. Of the 105 potential respondents who received the questionnaire, 21 of them answered, yielding a response rate of 20%.

Finally, as the study continued to develop, presentation of findings and targeted discussions with selected informants and peer academics were conducted, in order to validate and refine the findings and place them within the context of the field as a whole.

3. Results

3.1 Construction Waste

In many cases, production of waste is the result of inefficient use of materials. Waste production is also costly in terms of both financial concerns and environmental issues. The construction industry is affected by an inherent resistance to change, which could prove to be a significant challenge in the work towards waste reduction (Teo and Loosemore, 2001). The waste management hierarchy (Fig. 1) illustrates the preferred means for reducing waste in the construction industry (NSW EPA, 2014). The hierarchy consists of five levels: prevent, reduce, reuse, recycle, and disposal. The hierarchy is designed to be read from the top down: a measure assigned higher in the hierarchy implies a more sustainable solution. Concepts of the waste hierarchy appear to represent a significant potential for sustainability in the industry.

Several informants emphasise the importance of moving from a cradle-to-grave to a cradle-to-cradle approach and embracing concepts from circular economy in order to truly improve the handling of waste production in the construction industry.

3.1.1 Problematic waste fractions

The most significant waste fractions for the construction industry are cardboard and paper, plastic, and timber, plaster, and mixed waste (Kartam et al., 2004; SSB, 2019). Evaluating the generation of waste in the 161 new building projects confirmed previous findings: the largest or most problematic fractions were identified as timber (34.6% of total waste); mixed waste (27.3%); plaster (17.8%); paper and cardboard (2.7%); and plastic (2.3%). Paper, cardboard, and plastic do not account for large proportions of the total weight, but considering the low material densities of these fractions, it is reasonable to assume their volumes will be significant. The same fractions were also confirmed and highlighted by informants, in interviews and through the questionnaire.

Different amounts and fractions of waste arise in different phases of a project (NHP Network, 2016; Nordby and Wærner, 2017). 'Neste Steg' is a Norwegian framework for construction projects defined by Bygg21 (2015), similar to the RIBA Plan of Work (RIBA Architecture, 2020). Neste Steg specifies eight phases of a construction project: strategic definition; concept development; refining of concept; programming; production; delivery; operation and maintenance; and disposal of the facility. Furthermore, six sub-phases of the production phase can be defined (NHP Network, 2016): excavation; groundworks; framing; exterior finishing; internal finishing and fitting; and furnishing. The two classifications constitute the implementation framework of this study as summarised in Fig. 2.

3.1.2 Perceived potential for waste reduction

Interview informants were asked to identify the activities and processes producing timber waste. Some respondents reported answering the question based on their available statistics on a current project, while others answered based on their experience from previous projects. Carpentry, formwork, deliveries and rig work were identified as the activities that produce the largest amounts of timber waste. Similarly, informants were asked to identify perceived sources of plaster waste. The responses indicated that carpentry and the installation of inner and outer walls are the activities producing the largest amounts of plaster waste.

Most of the waste fractions were reported as arising from large portions of the production phase of a project. The interviewees suggested that to effectively reduce waste, not only should there be a focus on each of the fractions, but also on entire projects. Respondents generally considered large amounts of waste to be unnecessary, and some suggested that the problem is due to a lack of will, motivation, or knowledge.

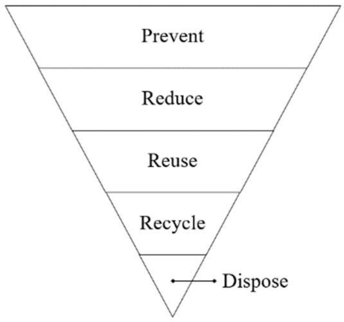

Fig. 1. The waste management hierarchy.

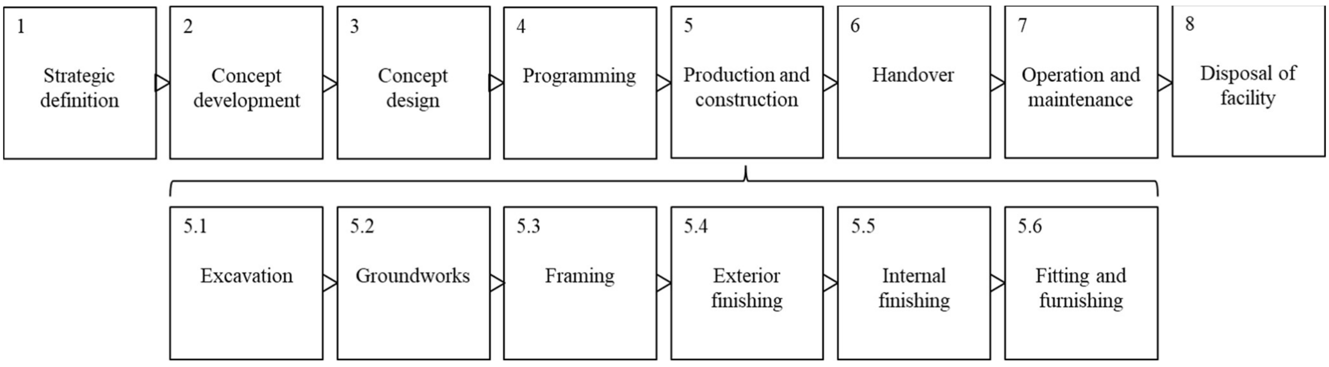

Fig 2. Phases of a construction project (Bygg21, 2015; NHP Network, 2016)

Most of the interviewees highlighted setting out clear objectives as important to create both engagement and a willingness to change. One interviewee believed that such objectives would be particularly valuable if combined with economic incentives, such as bonus-malus.

Incentive schemes that reward good actors and fines that deter careless actors were another measure suggested by numerous interviewees. Economic incentives are seen to be important both in the selection and implementation of measures in all levels of the project organisation and are supported by research (Azizi et al., 2015). One interviewee suggested that such a scheme could be used to reward measures for innovation in waste reduction, while another suggested that bonus-malus in contracts be allocated according to predefined objectives for waste reduction on site. Both emphasised the importance of involving all actors in the development of such solutions and saw a transparent process as essential.

A further general perception among the informants was that there is great value in establishing contact between all involved actors, and start-up meetings and joint reviews of the waste plans for the project or resource optimisation were mentioned as possible supplements to existing project waste plans. Strategically working towards a more collaborative project execution during the earliest project phases was also identified as of particular importance. Unfinished and imprecise contracts, as well as differing expectations between parties, were additionally highlighted as especially challenging with respect to waste reduction. The interviews further revealed that resistance to change is a major challenge on site.

In addition, most respondents mentioned the use of pre-cuts, prefabrications, and modular elements as possible measures. The resulting reduction of cut-offs was considered to be the greatest benefit, especially for timber and plaster. In this context, an interviewee stressed the importance of collaborative strategies in the early phases of a project to ensure it could meet the needs of all involved actors.

One informant emphasised the difference between preventing the production of waste and taking measures to utilise construction site resources after waste had been produced. Other interviewees argued that certain measures could reduce the construction waste on individual sites but would not be effective at the industry level.

Most respondents agreed on the importance of having a tidy, accessible waste station on site, with several interviewees mentioning the sufficient availability of containers as being especially important. The deterioration of materials on site because of weather, vandalism, or theft was also mentioned as a possible source of waste, while others considered the conscious or unconscious neglect of materials by workers to be of greater importance.

The design of a building itself was considered especially important. One informant mentioned late changes in design as one main reason that processes and activities must be repeated, or materials and elements discarded. This can happen due to late availability of information, or late change requests from the customer. Another interviewee mentioned complexity in the design of the building. Furthermore, unclear instructions and specifications were highlighted as problematic.

When asked which measures they believed to hold the most potential for waste reduction, interviewees responded that prefabrication, increased awareness, targeted building design, and contractual demands were among the greatest contributing factors to waste reduction on a construction site.

The systematic shift towards a more sustainable industry has led to an increasing number of techniques, tools, and solutions with the potential for waste reduction.

3.2 Established Tools for Waste Reduction

Certain tools are already established in the industry as suitable for construction site waste reduction. Lean construction, which draws concepts from lean methodology (Koskela et al., 2002; Womack et al., 1991), is a system that aims to maximise value by enhancing quality, improving efficiency, and reducing waste.

Conscious and sustainable design choices contribute to the reduction, and potentially, the avoidance, of waste – use of durable materials, standard sizes, and systems for increased adaptability, disassembly or reuse (Innes, 2004; Zero Waste Scotland, 2016). Measures built on the concepts of circular economy are seen to be an important factor also beyond specific design choices (NSW EPA, 2014). Reuse can be done on site, or elsewhere.

Research suggests a correlation between the level of collaboration in projects, and project performance in terms of cost, time, and quality, implying significant benefits in the use of collaborative strategies for waste reduction (Haaskjold et al., 2020). Increased industrialisation, for instance in the form of prefabrication has also proved to provide benefits in terms of reduced waste quantities on site (Tam et al., 2005).

Digitalisation is considered an important piece in the waste reducing puzzle, especially when aiming to realise the increased use of AI. An important part of the digitization process is the continuous development of tools such as building information models, that can store and display big amounts of data, even beyond the three dimensional digital twin (Charef et al., 2018).

3.3 AI in Construction Projects

Four categories of AI tools in the construction industry can be defined: machine learning (ML), knowledge-based systems, evolutionary algorithms (EAs), and hybrid systems (Akinade, 2017).

ML describes AI techniques that can learn from data (Tidemann, 2019). In the construction field, the ML approaches of artificial neural networks (ANN), support vector machines (SVM), and fuzzy logic (FL) appear to be the most widely employed (Akinade, 2017). Their main strength lies within their ability to handle uncertainty, and work efficiently with incomplete data. Knowledge-based systems mimic human problem-solving expertise to find solutions to complex problems, and possess strong explanation abilities (Sowa, 2000; Akinade, 2017). Commonly employed techniques include expert systems (ES), rule-based systems (RBS), case-based reasoning, and semantic networks (Akinade, 2017). EAs are based on biological evolution (Russel and Norvig, 2010); the techniques utilise an optimisation approach to find the most suitable solution (Dasgupta and Michalewicz, 2013). Among EAs are genetic algorithms (GA), ant colony optimisation (ACO), particle swarm optimisation (PSO), and artificial bee colonies (ABC) (Akinade, 2017). Hybrid systems combine two or more AI techniques to utilise the strengths and overcome the weaknesses of the individual techniques (Russel and Norvig, 2010). Robotics is a fifth, adjacent field. The techniques can all be employed for similar purposes, and can to some extent be said to, for instance, provide support for the human decision maker in design, scheduling, monitoring of progress, or assessing risks; the main difference lies within how the systems are developed, and the input they require.

Previous studies have been conducted on the use of AI in several areas: analysing, forecasting, and managing waste; examining the use of AI supporting the selection of an optimal landfill site and a waste-flow-allocation pattern, to minimise the total system cost related to waste disposal (Cheng et al., 2003); forecasting the generation of municipal solid and mixed waste (Abbasi and Hanandeh, 2016); developing a framework for an AI-based construction waste management system (Ali et al., 2019); and examining how the application of AI in the construction industry can be supported, highlighting the need for laying a sustainable foundation for advanced technologies in buildings (Adio-Moses and Asaolu, 2016).

A recent surge of interest in the topic of AI in construction has also led to an increased number of pilots and proofs of concept in the industry, both on the national and international scales. Experience and lessons learned have been further mapped through interviews, seminars, and discussions.

3.3.1 Waste reduction powered by AI

The interviews conducted illustrate a lack of common understanding and terminology, especially relating to certain technologies and techniques regarding the field of construction and information technology in general, and AI in particular. This can be observed in the informants having highlighted the need to establish unified terminology for effective communication. A general perception among respondents was that there is considerable potential in utilising AI in construction projects and on construction sites, but only two interviewees could point to concrete examples of this being conducted in practice at a larger scale. The interviewees had expectations of increased productivity, increased quality, and savings in time and cost, as well as waste reduction.

Problems with obtaining enough data, as well as data of sufficient quality, were identified as one of the barriers to increasing the use of AI. The relationship between the people involved and the technology was also considered to be critical for the successful implementation of AI-based techniques. One interviewee was especially interested in the potential of virtual reality and augmented reality. Relevant areas of use included tours and inspections; communication and cooperation among the actors in a project; preparation and training; and the possibility for consultants and specialists to visit a site before completion of the project. The majority of interviewees stated that the implementation process is particularly important, as it represents an important transition from traditional to more innovative methods. Fig. 3 illustrates the strategic framework developed for waste reduction powered by AI, drawn from all the findings of this study and validated through interviews, seminars, and discussions.

4. Discussion

The aforementioned techniques and tools can be utilised in new ways, enabling the reduction of previously challenging waste fractions. The following chapter will present the findings yielded from the methodological framework as described in the previous chapter, summarised in 18 recommendations for practical implementation of AI-focussed measures.

Early and explicit definition of appropriate targets for waste production seems to represent significant potential for waste reduction. At present, projects often define targets for sorting degrees; therefore, defining targets should be attainable for waste quantity, by volume or weight. Such a defined target could, for instance, be based on the indicator of kilograms waste per square inch. The indicator could then be divided among the project phases, among construction stages, among buildings within the same site, or within the same building. Including all actors in the project is recommended, for example, by utilising partnering elements such as start-up meetings and physical co-location; these can contribute to the development of a common culture and 'language' among the members of a project team. The target could be measured against other targets within the organisations of the involved actors, or those of other actors within the industry, which would potentially contribute to improved motivation. Appropriate targets could be defined through the utilisation of ML, specifically techniques for regression. An ML algorithm could estimate an appropriate value based on data from previous, comparable projects. Ideally, the algorithm would have access to sufficient amounts of good quality data. In theory, this could be conducted in the very early stages of a project, or during the concept design phase; however, to ensure the greatest possible amount of data, it is recommended that it be implemented during the programming phase (4).

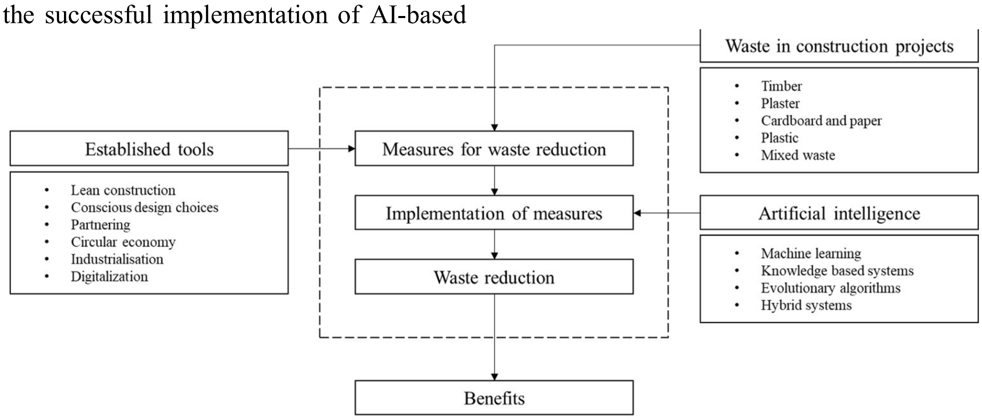

Fig. 3. Strategic framework for waste reduction powered by AI.

Similarly, an early and explicit plan for resource optimisation could be an important step towards more sustainable waste management. A resource optimisation plan should include an overview of which materials each actor plans to work with, an appraisal of potential sources of surplus material, and the ways in which any surplus material could be utilised by other actors on site –and it should be formed in the early stages of the project. A resource optimisation plan would provide benefits in the form of both increased awareness on the topic, and savings of time and money due to the presence of a dynamic plan. Plan development could employ such techniques as generative design in the form of GA, supported by ML, or ANN specifically, to evaluate and choose between alternative plans. The simplest form of generative design is topology optimisation, but more advanced algorithms are built around the same framework. Designs generated by such algorithms have been found to be far more efficient than those created by humans (McKnight, 2017), and are produced in a fraction of the time it takes for humans to create them. Nevertheless, algorithms rely on the quality of the input provided by the user. Furthermore, such an approach would, again, require access to sufficient amounts and quality of data, and it is therefore recommended that the approach be implemented during the programming phase (4).

In order to keep track of and create an understanding of, the full extent of a project's on-site waste production, continuous tracking of waste quantities is desirable. Tracking of waste quantities produced allows on-site production to be adjusted along the way, as a project approaches the defined target for waste production. This would be an important element in a holistic and integral waste management system, as production often happens simultaneously and in parallel at different physical locations. If a project succeeds in the tracking of waste quantities, continuous reporting of waste quantities should be next. Reporting could happen internally to the project team, or externally to staff members in other parts of the business. Similarly, to fully utilise the potential of tracking waste quantities, a project should strive to render a continuous visual presentation of waste quantities on site. Such a presentation could be displayed near any safety, health, and environment boards, in common areas, or near the site entrance. The goal would be to display the numbers to every worker on site, to provide an understanding of the size and scope of the current waste production. Presenting these numbers would be an important step in raising awareness and developing knowledge among personnel on site. For the continuous tracking of waste quantities, ML could be employed to manage sensors and computer vision. These tools could be installed inside and close to any waste stations and containers on site, and could contribute by weighing the waste or visually estimating remaining space. The biggest perceived benefit from such a system would be its ability to communicate with other systems, such as the project schedule system. A hybrid system based on ML and EAs could help estimate the next necessary emptying of containers and alert the responsible parties. For obvious reasons, this would need to be performed during the production phase (5). However, the system reports could be used for reference in future projects, to enable the knowledge to be utilised in earlier project phases. Existing, established tools – fuelled by AI or not – could be used to generate the reports and presentations.

To enable the reuse of materials and on site, defined routines for warehousing on site are recommended. The construction site needs sufficient capacity to maintain intermediate storage; tidy storage would also reduce the need for the placement of unnecessary orders, as it would be easier to track any already-available materials on site. Thus, defined routines for ordering materials would also be beneficial. A lean approach to the ordering of materials is one of many ways a lean mindset can be brought to construction sites. Maintaining such functions and routines may require significant resources. Similarly, increasing volumes and frequency of orders will increase transport emissions; therefore, such conditions should be considered for each project. Routines for warehousing on site could be designed based on information gathered by ML-supported sensors and computer vision. Moreover, routines could, again, be established based upon generative design techniques, such as utilising decision support in determining storage unit layout. The measure should be initiated during the programming phase (4) and continued through production (5). The ordering itself could technically be done by AI-powered tools, for example, based upon natural language processing. However, the results of this study suggest the more expedient option is likely utilising AI to estimate appropriate timing for the next order placement.

Training of all involved personnel seems to represent a significant potential for waste reduction. Proper training could reduce wasted time and potential savings in materials. Tools such as virtual and augmented reality, combined with a digital twin, enable virtual visits to the finished building – and the construction site itself – in advance. This could, for example, be utilised to instruct skilled workers in specific processes that are known to produce waste. Combining virtual and augmented reality with ML allows visitors to interact with their surroundings when exploring a digital twin. Ideally, the training of actors on all levels would happen independently of the individual project; if this is not the case, it is desirable to start the training as soon as all subcontractors and suppliers are procured, in the concept design (3) or programming (4) phases.

Several respondents pointed to the need for economic motivations, such as contractual arrangements based on bonus-malus, especially during the early stages of a waste reduction initiative. In such an arrangement, desirable performance and results are rewarded, whereas the actors who do not meet the required targets or expectations must pay. The biggest potential for AI utilisation would be using ML and generative design to identify fitting targets and prerequisites for such an arrangement. This would need to be implemented and established before contractual arrangements are finalised.

To fully benefit from all the benefits expected of digitalisation, and facilitate the increased use of AI, it is recommended to establish a digital platform for all actors in a project. This could serve as a platform for communication among all involved actors, but also as a hub for assembling all available information. Every actor should have access to any information relevant to their field. Establishing a digital experience-sharing platform in the early stages of a project would enable increased use of previous information and experience; this could become an important tool for the assembly and assessment of data from previous projects. Such a digital platform should be linked to a digital twin, as established in the design phases of a project. Ideally, the platform would be able to communicate with other systems, models, sensors, and programs within the project environment; this could make the platform an invaluable tool in the work towards a more sustainable operation. Such a platform would, naturally, be very complex, and built upon several tools; however, the foundational lines of communication could be built on a set of ES or RBS. The platform should be established as soon as all subcontractors and suppliers are procured, continued through the production phase—and brought into future projects, where it can be utilised as early as in the strategic definition (1) or concept development (2) phases.

Carrying out inspections during all phases of production (5) is desirable, as some type of surveillance will be crucial in the implementation and auditing of any other recommended measure. Inspections could also prove critical, to avoid faults resulting from a lack of communication among involved actors. During the early phases of the project, inspections could be executed with virtual and augmented reality, supported by AI. This could prove especially valuable in the earliest phases, as concepts, design, and plans appear the most distant in these stages. Such environments can also be used during later phases, provided the digital twin is updated throughout the project. This could reduce, or even eliminate, the need for physical inspections on site, as could the use of autonomous robots, computer vision, and sensors.

Functional layout planning of a construction site can increase efficiency and decrease faults, and can be achieved in numerous ways: defining areas for deliveries; establishing functional production lines for certain processes and activities; planning according to the availability of waste stations and containers; and planning according to the area covered by cranes. Layout planning should be powered by the use of generative design.

Increased use of digital tools to order more accurate quantities of materials is especially relevant for such waste fractions as wood and plaster and should be implemented as part of the concept design (3). These fractions are dictated by the design and architectural choices, to a greater extent than fractions like plastic. This measure, once again, depends on the continuous revision and availability of the digital twin. By marking orders and materials arriving on site according to the digital twin, waste could, potentially, be reduced even more drastically. Marking could, for example, be performed using barcodes, perhaps in collaboration with relevant suppliers. Such a system could be built upon a set of ES or RBS.

Several interviewees highlighted the potential of certain design choices during the early phases of project development. This is supported by the literature (Innes, 2004; Zero Waste Scotland, 2016). One approach would be to design for standardised elements, in which the building itself is designed to fit standard sizes of materials, such as given lengths of wood, or given areas of plasterboards. Another approach would be to design for the use of cut-offs, in which the possibility to use cut-offs produced on site is examined in the design phase. A third approach would be to design for shared geometry, in which several areas or sections of buildings are designed according to the same geometrical properties; this could even reduce the risk of wrongly manufacturing materials and elements, even further decreasing the amount of waste produced. These design approaches are especially relevant for such fractions as wood and plaster, as these materials are often delivered in standard sizes.

Table 3. Recommendations for implementation of waste reduction measures.

#	Recommended measures for waste reduction	Technique	Phase
1	Early and explicit definition of appropriate targets for waste reduction	ML (regression)	4
2	Early and explicit plan for resource optimisation	ML (ANN), EA (GA)	4
3	Continuous tracking of waste quantities	ML (ANN)	5 (3,4)
4	Continuous reporting of waste quantities		
5	Continuous and visual presentation of waste quantities on site		
6	Defining routines for warehousing on site	ML (ANN), EA (GA)	4,5
7	Defining routines for ordering materials		
8	Training of all involved personnel	ML	3,4
9	Contractual arrangements based on bonus-malus	ML (regression)	3
10	Establishing a digital platform for all actors in the project	ES (RBS)	1,2,3,4,5
11	Establishing a digital platform for experience-sharing		
12	Inspections during all production phases	ML (ANN), EA (GA)	5
13	Layout planning during all production phases		
14	Increased use of digital tools for ordering more accurate quantities of materials	ES (RBS)	5
15	Marking orders and materials arriving on site		
16	Design for standardised elements	EA (GA)	2
17	Design for the use of cut-offs		
18	Design for shared geometry		

According to interviewees, generative design has proven efficient in the design phase. The field of design seems to be of particular interest, both among academics and practitioners. The traditional design process is described by the informants as linear, reliable, and robust but with several drawbacks; for practitioners, one of the more obvious shortcomings is the use of cost and time resources.

A few interviewees suggested that time pressure in early project phases is problematic, as this often forces a project team to make decisions based on relatively little information. In this regard, techniques based on AI would be especially helpful, as, given the necessary input, they can swiftly generate hundreds of possible solutions. Some suggest that this could also help avoid certain late design changes that traditionally follow shifts in user demands. Decisions on the design of a building itself should be implemented as soon as all necessary information is available; this will naturally vary among individual projects, but concept development (2) could provide a basis.

Table 3 summarises the 18 recommended measures and their implementation. The recommended phases are numbered as per the framework in Fig. 2. Because most complete AI techniques and tools would comprise more than one form of AI and thus be hybrid models, the dominant system or technique is denoted.

An important topic of discussion when considering waste reduction is the definition of system boundaries for the analysis; for example, if the waste production is to be assessed for each project, or as a part of a bigger system and cycle. For a given analysis, certain measures will yield benefits depending on the system boundaries chosen for analysis. Such measures may reduce the amount of waste reduced on site, but not necessarily do so from a holistic perspective. One such measure is an increased degree of waste sorting on site, which will, naturally, reduce the amount of mixed waste, but not necessarily contribute to reducing the total amount of waste in the project. It will enable an increased degree of recycling, the second to last level in the waste hierarchy. Other examples include returning packaging to the respective suppliers following deliveries, and the increased use of prefabricated and pre-cut elements. The volumes of waste fractions such as timber and plaster will benefit from such on-site measures, but the waste will simply be moved elsewhere – even if the evidence suggests that the total amounts of waste will be reduced compared to production by more traditional methods.

Initially, the implementation of new measures and technology will require an investment cost. However, the consensus is that the savings provided by the same measures and techniques will exceed the costs within a relatively short timeframe. Implementation of such measures should be based on the assessment of expected benefits for each project.

5. Conclusion

The purpose of this study was to examine how AI can reduce waste on construction sites. The recommendations provide a practical approach to reducing waste, complementing the existing body of more theoretically based assessments. Through a broad research design based on analysis of existing literature, waste data, and involvement of actors from multiple parts of the value chain, the study identifies 18 recommended measures, presented in Table 3, for construction site waste reduction.

Benefits regarding increased sustainability are expected. A decreased carbon footprint, and decreased consumption of resources, are direct consequences of reducing waste on site. To accurately assess and understand the benefits associated with specific measures or combinations thereof, a mapping of actual implementation is recommended.

The increased use of AI in construction projects will require investment, especially during the early phases of implementation and introduction. As the cost of data processing continues to decrease and interest within the field continues to increase – bringing more available and commercialised solutions – it is reasonable to assume the cost will decrease dramatically.

The findings suggest that to fully utilise the potential of AI-based techniques, the construction industry would need to build upon existing methodologies and strategies; however, it would need to eventually reinvent and redefine the most traditional project models, contracts, business models, and enterprises. This is a comprehensive task and should involve key actors in all parts of the value chain. Another useful undertaking would be to study in closer detail how data of sufficient quantity and quality should be collected and structured to enable AI to efficiently utilise it.

A valuable option for further work could be to examine the implications that identified measures will have for other actors: for example, how certain design choices may affect other architectural principles and solutions. Another extension of the theoretical approach of this study could be a case study to further investigate the identified measures and test them in practice. Finally, the measures for certain processes or activities could also be selected for testing, providing an opportunity to vet any effects of each measure – or combinations of measures – before the measures are implemented on a larger scale.

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