

**Applying Lean Digital Solution in Construction
management: optimization of rebar use and cost reduction**

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**NAZARBAYEV
UNIVERSITY**

School of Engineering and Digital Sciences

In partnership with

Graduate School of Business

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May, 2025

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Declaration

We, Samal Berikbaikyzy, Aknur Temireyeva, Shynggys Turarbek and Adil Kaskyrbayev, declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the authors' original work. The thesis has not been previously submitted to this or any other university for a degree and does not incorporate any material already submitted for a degree.

Signature (s):

Date:

Abstract

This capstone project addresses material use inefficiencies in the construction sector of Kazakhstan by designing and implementing an optimization tool for digital rebar cutting in the example of Company A. The digital tool optimizes the combinations of rebar lengths to be used and cut by applying a genetic algorithm and its mathematical modeling to reduce material waste and procurement cost. In the case study of a school project demonstrated to test and verify the digital tool, the total waste reduction was 50.5%, while the efficiency of the used material reached up to 91.4%. A strategic plan for integrating the tool was developed, which included a phased deployment having basis on ADKAR (Awareness, Desire, Knowledge, Ability and Reinforcement) change management model, stakeholder governance via a RACI matrix (Responsible, Accountable, Consulted, Informed), Key Performance Indicators (KPIs) for monitoring, risk management plan, and training strategies for adoption. The project is aligned with the national policies and sustainability goals of the “Kazakhstan 2050” strategy as well as circular economy initiatives. Recommendations for future exploration include fostering industry innovations such as Building Information Modeling (BIM) incorporation and modular construction, extending to multi-variable applications like drywall, as well as fostering digital transformation and use of digitalization platforms through public-private partnerships. This project shows how lean digital solutions drive sustainable transformation in the construction sector of Kazakhstan.

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We would also like to acknowledge Company A for providing the opportunity, resources, and real-world project environment necessary for testing and validating our rebar optimization tool. Their collaboration and practical insights were instrumental in ensuring the relevance and applicability of our work.

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This project stands as a reflection of collective effort, dedication, and the shared pursuit of innovation in advancing sustainable construction practices in Kazakhstan.

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List of Abbreviations

ADKAR - Awareness, Desire, Knowledge, Ability and Reinforcement

AI - Artificial Intelligence

BFD algorithm - Best-Fit Decreasing algorithm

BIM - Building Information Modeling

CDW - Construction and Demolition Waste

CE - Circular Economy

CIS - Commonwealth of Independent States

CSP - Cutting Stock Problem

CSS - Cascading Style Sheets

CWR - Construction waste reduction

GA - Genetic Algorithm

GDP - Gross domestic product

GIS - Geographic Information Systems

EU - European Union

FAQ - frequently asked questions

FFD - First-Fit Decreasing algorithm

HTML - HyperText Markup Language

HTTP - HyperText Transfer Protocol

ILP - Integer Linear Programming

IoT - Internet of Things

IT - Information technology

JIT - Just-in-Time management

JRC - Joint Research Centre

KPI - Key Performance Indicators

LCM - Lean Construction Management

LDC - Lean Digital Construction

LLP - Limited Liability Partnership

LP - Linear Programming

LPS - Last Planner System

LSTM - Long Short-Term Memory

RACI - Responsible, Accountable, Consulted, and Informed

ROI - Return on Investment

SOP - Standard Operating Procedure

VSM - Value Stream Mapping

UK - United Kingdom

URL - Uniform Resource Locator

1. Introduction

Kazakhstan’s construction market has been experiencing rapid growth, having a market size of \$22.6 billion in 2023 (Competitive Landscape and Forecast to 2028 - H2 Update, 2024). The construction industry currently contributes 5.6% to Kazakhstan's GDP, includes around 53,000 enterprises operating within its framework, and employs approximately 670,000 people (Official Information Source of the Prime Minister of the Republic of Kazakhstan, 2024). Kazakhstan’s construction sector involves 52,096 stakeholders in primary material production, secondary material extraction, construction, waste processing, and trade. 84% of them deal with construction activities, shown in Figure 1.1 (Torgautov et al., 2021).

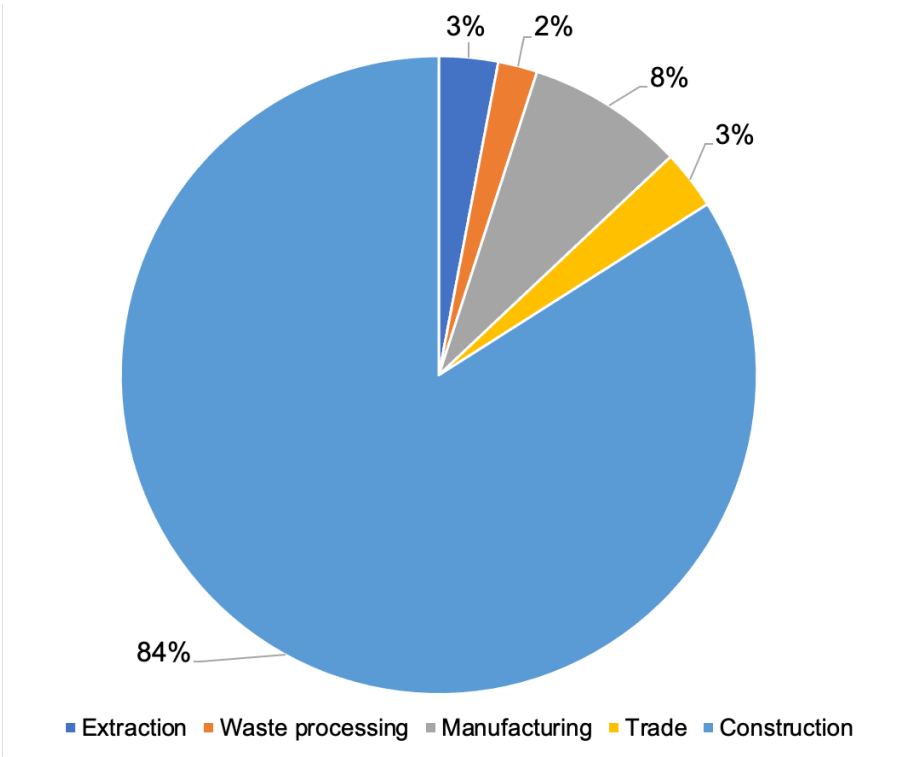


Figure 1.1. Stakeholder numbers in the construction sector by activity types (adopted from Torgautov et al., 2021)

In this regard, Kazakhstan’s government has been a key player in developing the construction industry. Firstly, Kazakhstan encourages banks to provide housing loans to socially vulnerable populations through the Mortgage Loan Guarantee Fund. Mortgages are a major factor in house affordability. State preferential lending programs such as “Affordable Housing 2020,”

“7-20-25,” “Nauryz Housing Program,” “Nurly Zher” have been launched to increase the stock of living space and give access to affordable housing (Mendigaliyev, 2023; Prime Minister, 2024). According to the Agency for Regulation and Development of the Financial Market (Figure 1.2), the growth rate of banks’ mortgage portfolios increased by more than 30% between 2019 and 2020, and reached 2.45 trillion tenge in 2021 (Mendigaliyev, 2023). Moreover, the government has planned to allocate 965 billion tenge for housing construction and infrastructure in 2025, expecting to deliver 41,000 new flats for 160,000 citizens (Official Information Source of the Prime Minister of the Republic of Kazakhstan, 2024).

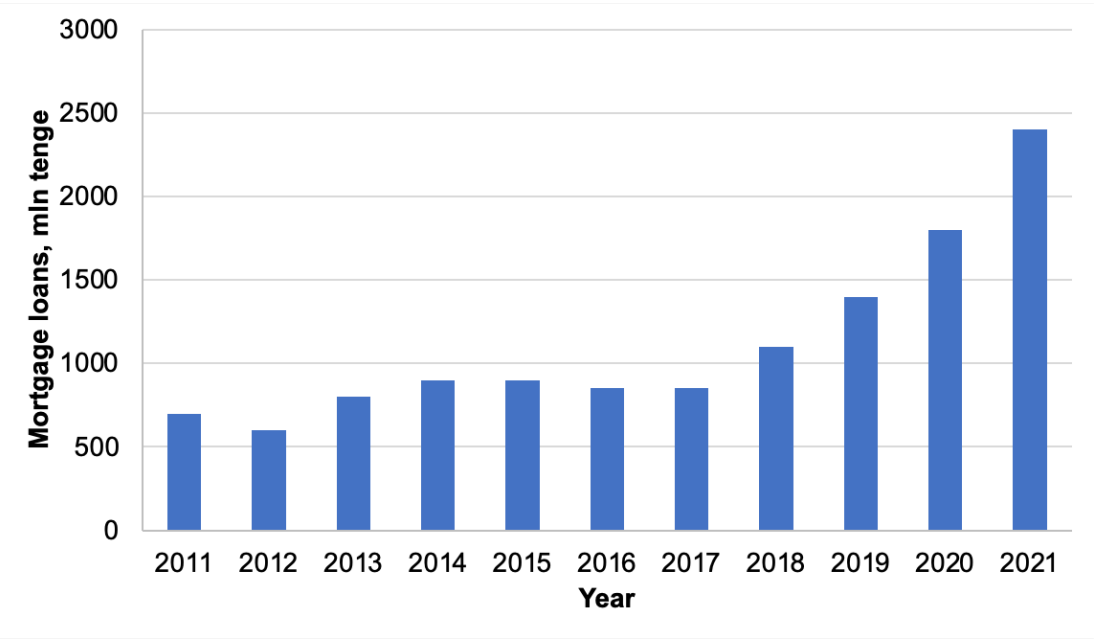


Figure 1.2. Mortgage lending growth rate (adopted from Mendigaliyev, 2023)

Large-scale infrastructure initiatives, such as the “Nurly Zhol” program, have significantly strengthened Kazakhstan’s construction industry. With a budget of USD 9 billion, the plan focuses on modernizing and expanding the nation's transportation and IT infrastructure (Nurly Zhol, 2020). This program includes the construction and reconstruction of 10,000 kilometres of highways and the repair of 11,000 kilometres of road network, as well as investments in trains, ports, and airports (Ferhat Karaca & Aidana Tleuken, 2023).

However, the growth of construction activities in Kazakhstan also brings challenges in terms of sustainability, resource management, and cost optimization. Global trends emphasize the importance of improved sustainability in building, with a focus on resource optimization,

recycling, and the use of innovative technologies such as Building Information Modelling (BIM) and prefabrication (Yu et al., 2021). Notably, approximately 35 thousand tonnes of construction waste were generated in 2021, and the total amount of waste in Kazakhstan is estimated to be 9 million tonnes (Ferhat Karaca & Aidana Tleuken, 2023). While European Union countries recycle up to 90% of construction and demolition waste (CDW), Kazakhstan’s recycling rate is only 2.96%, with the majority of waste ending up in landfills or informal waste sites (Ferhat Karaca & Aidana Tleuken, 2023). Studies from China and Hong Kong have shown that effective waste management solutions, such as on-site sorting, the use of circular economy ideas, and innovative design practices, can dramatically reduce waste generation (Li et al., 2020; Yu et al., 2021). Kazakhstan can use such insights to manage its expanding waste issues.

In this case, reinforcing steel (rebar) plays a crucial role in construction projects, often accounting for a significant portion of total costs — approximately 20% (Rahimi & Maghrebi, 2022). Poorly designed layouts and inefficient cutting plans frequently lead to unnecessary waste, increasing both material expenses and environmental impact. Using advanced methods like combining layout design with accurate cutting strategies helps reduce waste and minimize costs significantly. Real-world applications show that mathematical models can improve cutting processes, making material use more efficient. This highlights the critical need to coordinate design and construction phases, emphasizing the importance of adopting innovative techniques for better rebar management.

1.1. Problem statement

For this capstone project, data was obtained from a construction company, referred to as “*Company A*” to ensure confidentiality in accordance with the company’s request. Company A is one of the largest investment and construction holdings in Central Asia. It is included in the top 200 of the ENR Top 250 Global Contractors rating of the largest construction companies in the world. Headquartered in Kazakhstan, the company has an extensive portfolio, including residential, infrastructure, and industrial development projects.

According to the Deputy Minister of Ecology and Natural Resources, Kazakhstan generates more than 4.1 million tonnes of municipal waste each year, yet only 24% of it is recycled, underscoring significant inefficiencies in waste management (Kwan, 2024). A substantial share of this waste comes from construction and demolition activities, much of which is disposed of in

landfills due to a lack of adequate recycling facilities (Kwan, 2024). Therefore, the government has launched initiatives to upgrade eight waste processing plants and construct 37 new facilities (Ewing & Denys, 2024). However, targeted solutions within the industry are necessary to effectively tackle material optimization challenges.

The construction projects of Company A generate significant amounts of waste, resulting in financial losses, work and planning inefficiencies, and environmental concerns. According to survey results conducted with the executive of the strategy department, the top categories of waste generated on the construction site are: metallic waste (rebar) (21% of total waste), concrete-based materials (10% of total waste), and insulation and asbestos materials (5%). The total reported waste volume reached 1,450 tonnes, with rebar accounting for 300 tonnes per construction project.

The survey identified several key causes of waste generation shown in Figure 1.3. Errors in material calculations, poor planning, material non-compliance with project requirements, and insufficient personnel qualification are major contributors to waste handling. While concrete-based materials are only associated with materials not meeting specifications, metallic and insulation and asbestos waste mainly depend on calculation and planning.

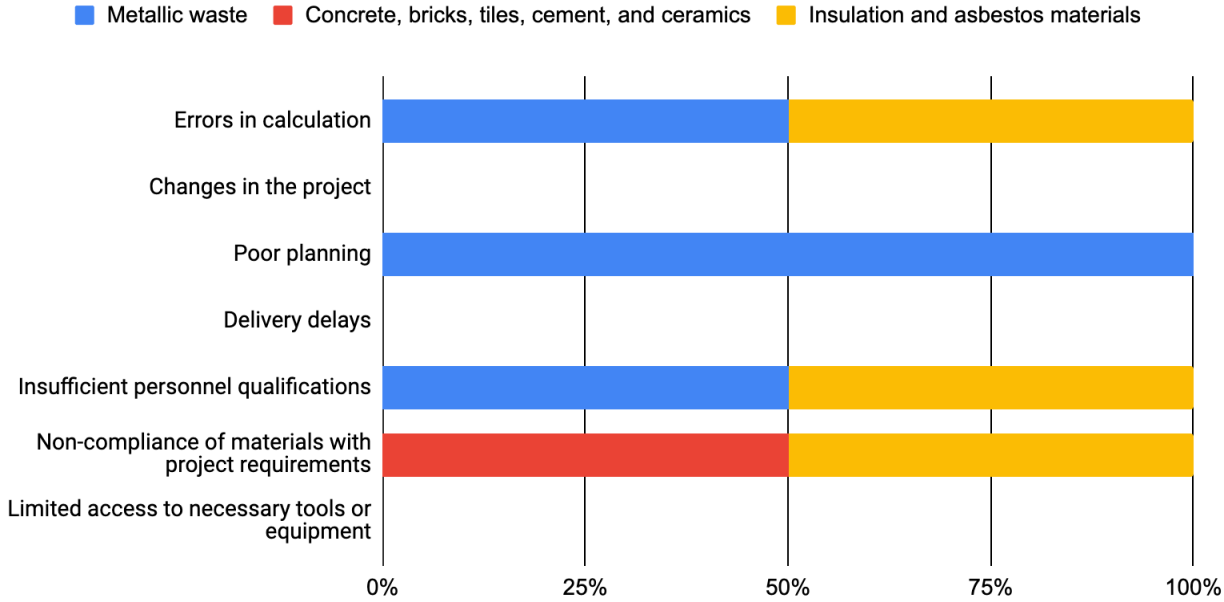


Figure 1.3. Causes of waste generation

These inefficiencies, in turn, have a direct financial impact, including material purchase costs, storage and disposal expenses, and work schedule shifts (Figure 1.4). Moreover, studies

indicated that rebar is one of the most expensive types of material waste in construction (nearly 20% of the total structural costs) (Rahimi & Maghrebi, 2022). The survey further highlighted that waste mismanagement has frequently led to budget overruns, especially for concrete and rebar waste.

Moreover, the current waste management methods of the company, which mainly involve storing unused rebar for potential future use, do not effectively reduce costs or maximize resource efficiency. Kazakhstan’s Environmental Code requires the adoption of sustainable construction practices (Chambers and Partners, 2024). However, ineffective material management strategies create obstacles to compliance and lead to financial losses. To address the urgent need for both sustainability and cost efficiency, the capstone project will focus on developing a data-driven framework to optimize rebar waste management and reduction. The solution incorporating Python software will provide practical solutions for Company A.

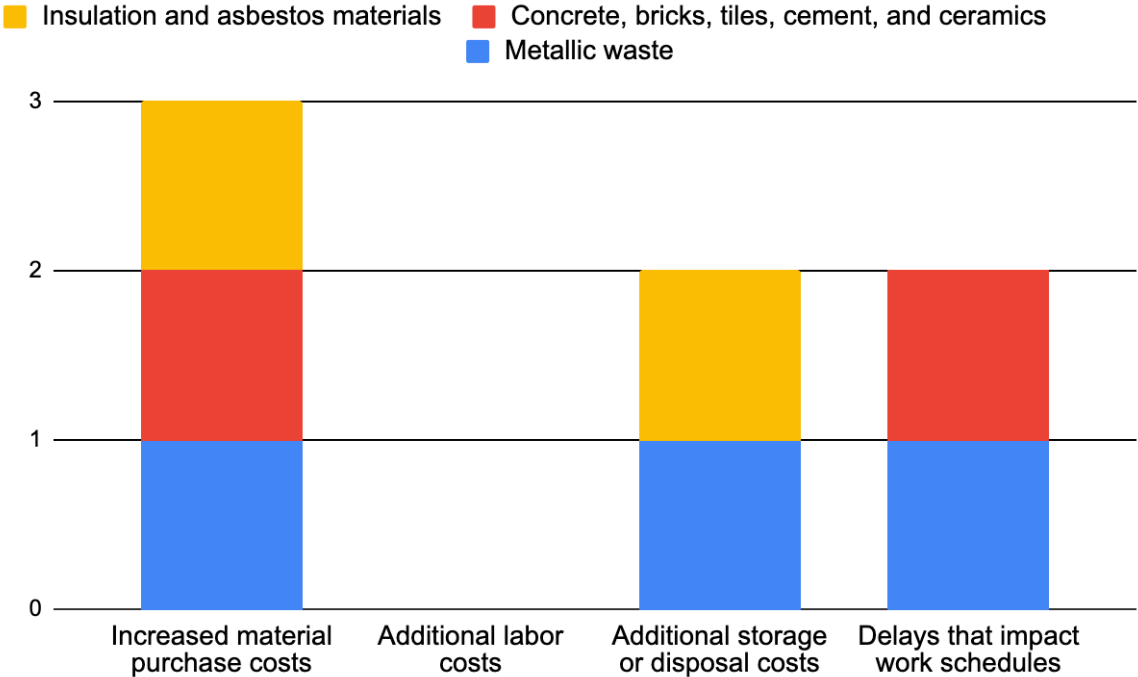


Figure 1.4. Impact on project process

1.2. Project scope and objectives

The *scope* of this project lies in the research and development of a digital solution for a rebar use optimization problem in the construction industry. The project work incorporates automated algorithms and Building Information Modeling (BIM) as methods of solution for the identified issues and also provides a comprehensive review on its practical application in resource management and cost reduction from real-life examples.

Within the given resources, a tool for streamlining and integrating the proposed digital solution into Company A's architecture and construction workflow constitutes a design framework for implementation. Beyond that, for the benefit of scaling the proposed solution into Company A's operations, a guideline is provided for the implementation team to effectively engage with project managers, procurement teams, construction engineers, and other stakeholders. An analysis of the long-term impact of digitalization for Company A highlights valuable insights into the strategic foundation for prospective advancements in construction through the identification of the potential cost savings in the form of material waste reduction and process efficiency gains. This further supports the adoption of Lean Digital Construction (LDC) practices across construction companies of Kazakhstan. Overall, the capstone project has following *objectives*:

1. Develop a digital rebar cutting optimization tool by implementing and correctly choosing a best-fit algorithm, through which rebar waste is minimized;
2. Enhance construction efficiency and resource management by reducing material waste and offcuts by optimizing rebar cutting patterns and providing data-driven insights;
3. Analyze cost reduction and sustainability benefits by evaluating the financial and environmental impacts of optimized rebar cutting through assessing effect on construction budgets and reduction of scrap material, carbon emissions resource utilization;
4. Create an implementation guideline for industry adoption by developing a step-by-step roadmap for integrating the cutting optimization tool into construction workflows;
5. Propose future digitalization strategies by identifying how artificial intelligence (AI), Internet of Things (IoT), and automation can further enhance rebar cutting process efficiency and explore the ways in which the digital tool can promote digitalization in the construction industry of Kazakhstan.

Moreover, this capstone project, in the example of the digital tool developed in the scope of this work, aims to highlight the importance of the digitalization not only for Company A but also for the whole construction industry of Kazakhstan as a small step for digital transformation.

2. Literature review

2.1. Classification of waste management in construction

Waste control and handling, also known as construction and demolition waste (CDW) management, is a major concern in the construction industry due to its negative impact on different aspects of sustainable urban development like resource efficiency, circular economy, and environmental safety (*Construction and Demolition Waste*, n.d.). Various forms of CDW include concrete, bricks, wood, glass, metals, plastics, and anything related to the residue or debris from the construction and demolition operations of diverse infrastructure types, such as buildings, road networks, and their maintenance (Past et al., 2023). For instance, CDW encompasses a third of all the waste generated in the European Union (EU) alone, a testament to its major environmental influence (*Construction and Demolition Waste*, n.d.). Consequently, a proper classification and the utilization of effective means of waste management such as reduction, reuse, and recycling can mitigate the associated detrimental effect on the environmental and economical sustainability.

Although the form and diversity of CDW in Kazakhstan is the same as in the EU, the lack of proper monitoring and control over the generation and recycling of the residue materials significantly increases the management difficulty (Karaca & Tleuken, 2023). The improvement of CDW management in Kazakhstan is the objective of recent industrial efforts, specifically the establishment of specialized landfill sites and recycling facilities that aim to achieve a 95% recycling rate over eight years. The progress in that area has been slowed down due to the severity of the recovery rates of construction waste in Kazakhstan, remaining as low as 2.96%, compared to 90% of the EU (Karaca & Tleuken, 2023).

The rapid growth of the construction industry due to urbanization increases the demand for proper CDW management to be prioritized in the country as the tripled production of construction materials is making the situation worse only (Torgautov et al., 2021). According to the research, only 2% of construction companies are involved in waste collection and recycling, while only 5% of 19,924 landfill sites in Kazakhstan meet environmental standards; 73% of which remain unauthorized (Torgautov et al., 2021). In order to commence improving the situation in the country, proper classification of CDW according to global standards is necessary.

Globally, CDW classification is a well-established practice, where materials are categorized based on their composition and potential for reuse or recycling (Rayhan & Bhuiyan, 2023).

Usually CDW classified as:

1. *Inert waste*: concrete, bricks, and ceramics, which are often recycled as aggregates;
2. *Non-inert waste*: wood, plastics, and metals, which can be reprocessed into new products;
3. *Hazardous waste*: asbestos, solvents, and chemicals, requiring specialized treatment.

In the EU, advanced frameworks for CDW classification and management have been developed, focusing on circular economy principles (Silva et al., 2014). Germany, Netherlands and Japan are considered to be leaders of CDW management. For instance, Germany and the Netherlands achieve recycling rates of up to 90% by employing rigorous policies, implementing efficient sorting technologies and innovative technological advancements (Balasbaneh et al., 2024; *Construction and Demolition Waste: From Downcycling Towards Closed- and Open-loop Recycling*, 2022; *Construction and Demolition Waste (CDW) & Raquo; Collectors*, 2018). Similarly, Japan has implemented a highly efficient CDW classification and recycling system through a combination of technological innovation and community-focused practices, achieving a 97% recycling rate (Balasbaneh et al., 2024).

At the same time, there remain several challenges affecting the recycling system and rate. One of the primary challenges in CDW classification is the heterogeneity of waste streams, which makes sorting and recycling processes complicated (Balasbaneh et al., 2024). In this regard, automatization of waste through the use of machine learning and artificial intelligence (AI) are being increasingly implemented. For example, deep learning techniques such as Long Short-Term Memory (LSTM) networks and image processing algorithms are shown to be promising in accurately identifying and sorting CDW materials (Samal et al., 2025). Moreover, Building Information Modeling (BIM) and Geographic Information Systems (GIS) are being integrated into waste management frameworks in order to enhance data collection and classification accuracy (Balasbaneh et al., 2024).

2.2. The need for CDW minimization: economic and environmental perspectives

Large amounts of waste are produced on construction sites, which impacts project schedules, economic efficiency, and environmental sustainability (Alhawamdeh, 2020). Waste minimization has become a key construction management component due to increased awareness of building waste's adverse effects on the environment and financial costs. The impact of CDW can be looked at in two categories: project level and national level, both of which are discussed in the capstone project (Alhawamdeh, 2020). At project level CDW influences on stakeholder profitability, reputation, and project performance, while at the national level, dealing with waste and associated issues puts a financial strain on governments and causes environmental difficulties (Alhawamdeh, 2020). Thus, effective management of CDW and the waste minimization is vital to optimize resource use, and minimize project costs.

In economic terms, minimization of CDW leads to substantial cost savings for construction projects by reducing material costs, waste disposal fees, and potential penalties (Osmani, 2012). In the report written at the national level in the United Kingdom (UK), it was found that reduction of waste allowances by just 1-2% would result in cost savings of £15-31 million of construction products (Adams et al., 2008). In terms of tonnage, this reduction is equivalent to 104,000 to 208,000 tonnes of material based on their estimated 10.5 million tonne annual wastage allowance (Adams et al., 2008). It is also supposed that CDW minimization contributes to economic growth by creating jobs in recycling and waste management sectors and reducing the cost of raw materials as was implemented by the US recycling industry (U.S. Environmental Protection Agency | US EPA, 2025). At the same time, the transition towards a circular economy (an economic model focused on minimizing waste and maximizing resource efficiency by promoting recycling, reuse, and sustainable material management to create a closed-loop system) for CDW requires balancing short-term economic costs with long-term environmental and financial benefits for companies, thus higher landfill taxes and financial incentives for recycling can encourage more sustainable CDW management (Caro et al., 2023). Table 2.1 exemplifies some of the research results with environmental and economic impact of implemented and proposed solutions in real-life cases.

Table 2.1. Study on economic and environmental impact of solutions in real life

| Case study | Solution | Impact | Reference |
|-------------------------------------|--|---|---|
| UK Construction Projects | Prefabrication and reuse of on-site waste | Savings of £15-31 million of construction products at a national level | (Adams et al., 2008) |
| US Recycling Industry | Recycling CDW into new construction materials | Reduces the cost of raw materials by 20-30% | (U.S. Environmental Protection Agency US EPA, 2025) |
| Brussels city | Waste reduction, modular construction, and reuse of building materials | Reduction of the carbon footprint by 7-25% and 10-26% of the material footprint | (Christis et al., 2019) |
| South-Eastern Queensland, Australia | Recycled concrete as an aggregate | Positive net benefit of \$30,916,000 per year | (Tam, 2008) |
| La Paz, Bolivia | Hybrid organization of stationary and mobile recycling facilities | Estimated 56.1-71.1% of inert aggregates can be recycled | (Ferronato et al., 2022) |

In environmental terms, the construction industry in Hong Kong only is responsible for the disposal of an average of about 4000 tonnes (25% of total disposal) of CDW at landfills per day in 2019 (Yu et al., 2021). The recovery rate of CDW depends on the country, even though it is estimated that 35% of the world's CDW is disposed of in landfills (Soto-Paz et al., 2023). Overall, the improper management of CDW poses significant environmental risks such as the contamination of surface and underground water sources due to the presence of heavy metals, organic, and inorganic compounds, leading to groundwater losses of up to 1.5 kilotonnes and reduced soil fertility (Soto-Paz et al., 2023). Additionally, the disposal and incineration of CDW

contribute to climate change and air pollution (Papadaki et al., 2022). Recycling CDW with advanced technologies can save approximately 264 kg CO₂ per tonne of waste, with a potential total reduction of 33 million tonnes of CO₂ annually in the territory of the EU (Caro et al., 2023).

2.3. Origins and causes of rebar waste

Rebar (reinforcing steel bar) is a critical material in construction, providing tensile strength to concrete structures. However, rebar waste is a significant issue in the construction industry, contributing to material inefficiencies and increased project costs. Unlike other construction materials, rebar waste is often non-reusable and non-recyclable due to its specific structural requirements and potential damage during demolition (Ghisellini et al., 2017). This section explores the origins and causes of rebar waste and highlights strategies for its minimization, which will be a focus of this capstone project.

The construction project requires efficient management of material resources, the consequences of which are deeply associated with the generation of construction waste (Kwon et al., 2021). In many instances, the planning process includes the proper usage of acquired material and performs estimations based on the amount of material needed per project. Whilst the general procedures are kept and accounted for, the complications in terms of micromanagement of the procured rebars gives rise to the inconsistencies and mismatch of actual construction component parameters that are required at the site. The lack of an accurate model for the designation of rebar sizes and the subsequent cutting process leads to the independent handling of the process by the engineers to the best of their judgement (Zheng et al., 2019). In such instances, the involved human factor leads to the unpredictable results and the accumulation of leftover rebars that were not cut in compliance with the specified guidelines. Moreover, the excess usage of rebars for lap splicing in the design and implementation stage to ensure the continuity between them typically leads to inefficient use of construction materials due to the overlapping length of the rebars. Aside from inflicting economic loss, poorly structured lap splices may obstruct swift distribution of concrete in the congested areas, compromising its structural integrity. The optimization of lap splicing would, therefore, notably increase the efficacy with which the materials can be used in the overlapping sections, without compromising its stability.

The risk of delaying building construction due to insufficient resources is high if the coordination between design and procurement divisions is not in sync. Excluding the potential

expenses on labor work and equipment maintenance, the realization of the project is significantly delayed, thereby putting the company profile at risk. Durdyev and Hosseini (2019) have identified the “material shortage” to be one of the main causes of construction delay, in which the procurement process is recognized as one of the major causes. Consequently, overshooting the safety margins in terms of procurement is frequently observed and this leads to substantial rebar waste after the construction completion. Even at the time of project execution, the excess rebars are subject to erosion over time and often mixed with other leftover materials to be disposed of in the landfills (Zheng et al., 2019). Hence, it incurs not only a financial loss for the contractor, but also a significant crisis for the environment and its conservation. In light of these issues, the rebar waste needs to be minimized by using advanced models further described in the following sections.

2.4. Existing effective methods on construction waste reduction

Construction waste reduction (CWR) is one of the important aspects in construction management which refers to the reduction of hazardous waste in construction. Even though it is crucial for safety measures, the CWR management system in many countries lacks emphasis on a suitable source plan (Liu et al., 2020). There are several factors that influence the CWR, identifying which to focus on to improve the case. According to Liu et al.’s study, there are nine key factors which impact waste reduction such as professional ethics of stakeholders, waste management behavior, waste sustainability, government subsidy, construction contract, construction material transportation, construction material site management planning, construction material storage, and construction site operation (Liu et al., 2020).

Rebar waste management depends on factors such as construction material site management and construction site operation due to their sorting and optimizing nature. Prior to implementation, the rebars are procedurally cut to minimize the losses, known as the cutting stock problem (CSP) that will be discussed in detail in the next section. In addition to CSP, methods of waste reduction such as prefabrication, reuse and recycling of excess rebars can be implemented (Liu et al., 2020). Prefabrication is one of the increasingly advocated methods of handling construction processes with fewer arising problems, such as cost estimations, time delays, worker safety concerns and quality of the implemented materials over the period of construction. The main strategy behind the reduction of waste using this method lies in the earlier preparation of construction materials with high accuracy at the specialized facility for more convenient

installation at the site itself. For instance, a life cycle analysis of materials and the construction process with prefabrication in Hong Kong by Lu and Yuan (2013) reveals that the waste generation is lower than that of traditional construction methods. The public sector has experienced substantial preservation of economic capital in construction materials by using this method. Conversely, the private sectors seldom made use of this strategy, mainly due to the construction design fluidity and additional expenses for transportation fees. The prefabrication method does not allow for a freedom of change of the ordered parts, highlighting the need for stable market conditions usually observed in the public sector (Lu & Yuan, 2013).

Recycling is another prospective method of reducing the residues left behind from the locally processed reinforcing bars that are cut and bent to meet the construction requirements. In many instances, recycling the leftover rebars – rather than reusing them for secondary reinforcements – is a more effective approach for mitigating the risk factor associated with satisfying the regulatory structural and safety standards. Cutting, bending, and other handling of the original rebars may often result in the degradation of the remaining rebar quality, preventing their future application. Consequently, a substantial 3-5 % of initial rebar mass goes to waste and can be repurposed into other products necessary for smaller work scope, like nails, further contributing into the circular economy and conserving the environment (Kwon et al., 2021). Sherov et al. (2021) have also noted that the waste produced from companies such as Limited Liability Partnership (LLP) “NORD Prom NS” (Temirtau city), LLP “ZBI-5” (Aktas city) and other manufacturers of the Republic of Kazakhstan reach an average value of 2%, further highlighting the need for sustainable recycling. While the cost of recycling and repurposing is not cheap compared to traditional means of waste disposal, it can offer potential economic returns. Abdullah et al. (2024) have estimated that on the global-scale the recycling of 0.01-0.05 billion tons of rebar waste can generate USD 5.76-28.8 billion by repurposing rebar waste into by-product steel. On the scale of Commonwealth of Independent States (CIS), the calculated remanufacturing profit in Russia for each 0.01 million tonne/year is equal to USD 5.76 million. Similar trends can be applied to Kazakhstan and its growing construction industry.

2.5. Existing effective algorithms on rebar cutting process

Creating efficient rebar cutting systems functions as a key operational demand in construction management while delivering important impacts on construction material usage and

project costs. Various computational solutions exist to solve the rebar cutting stock problem (CSP) and differ according to the specific problem conditions and requirements. This section examines existing industry-used and research-based algorithmic solutions which demonstrate maximal effectiveness.

The rebar cutting problem finds its answer through mathematical rigorous solutions built from linear programming (LP) and integer linear programming (ILP) formulations. The fundamental column generation method Gilmore and Gomory (1961) remains standard practice for modern implementations that lead to controlled waste reduction outcomes of 12-18% according to Wang et al. (2024). However, computational complexity limits the use of these methods for problems with more than 50 segment types as solution times escalate rapidly with increasing the types of segments (Rahimi & Maghrebi, 2022).

On the other hand, Genetic Algorithms (GAs) deliver high effectiveness for resolving complex rebar cutting problems. Metaheuristic approaches show performance reliability across different project scales because they use biological evolution principles (Holland, 1975). Standard implementations apply 50 to 200 members for each genetics-based run. The majority of solutions finalize their stabilization process during a period of 100 to 500 generations. The study revealed a waste reduction of total rebar usage by 17.76% and less than 1% waste remained in the cutting process (Widjaja et al., 2023). Key advantages include:

1. Adaptive exploration: maintains diversity through mutation rates of 0.5-2%;
2. Constraint handling: incorporates diameter-specific rules through customized fitness functions;
3. Scalability: processes 25,000 rebar rows in <150 seconds (Wang et al., 2024);

The combined utilization of BIM integration with GA in current projects delivers material utilization reaching 98.2% for educational facilities (Rahimi & Maghrebi, 2022).

The rebar cutting problem receives efficient computational solutions through greedy algorithms by letting each decision point adopt locally optimal moves. Despite their inability to locate absolute best solutions these simple methods remain very important for practical usage owing to their fast delivery results. Waste reduction from 8-12% can be achieved through the First-Fit Decreasing (FFD) algorithm which sorts required segments by length in descending order for assignment according to the research of Johnson (1974). The processing system handles 10,000

segments through efficient data processing that completes operations within five seconds of total computation time.

Best-Fit Decreasing (BFD) shows better efficiency than FFD since it selects segments for placement within the optimal empty locations on existing rebars. According to Korte and Vygen (2012) BFD method cuts material waste to 7-10%. Basic greedy methods for industrial applications refined their strategies by incorporating look-ahead tactics and extra enhancements. The results from Wäscher et al. (2007) show that these enhanced greedy heuristics operate in real construction scenarios with 20,000 segments to process them in about thirty seconds while creating material waste between 6-9%. The evaluation of greedy approaches shows that they use 8% of exact optimization computations to achieve 85-90% of their optimization performance according to Rahimi and Maghrebi (2022).

Construction companies across the industry have begun using hybrid optimization frameworks that unite various algorithmic methods because each method has its own inherent limitations. The Genetic Algorithm works for extensive global exploration during 100-200 evolutionary cycles after which it hands over fine-tuned solutions to the Best-Fit Decreasing algorithm as part of their collaborative framework. Research conducted by Wang et al. (2024) demonstrated that combining GA with greedy methods led to waste minimization of 22.48% when applied during tests of actual construction activities.

Linear programming serves as an initial solution mechanism in alternative hybrid systems that solves relaxed problem formulations followed by First-Fit Decreasing heuristics for converting fractional solutions to practical cutting patterns. Research done by Wäscher et al. (2007) showed that combining LP with greedy approaches produced results with less than 5% optimality gaps alongside considerable reductions in computation time. The most significant results stem from integration between Building Information Modeling (BIM)-integrated systems that utilize three-dimensional project visualization to manage optimization algorithms. BIM-integrated solutions documented the implementation of total rebar costs reductions by 26.6% while also achieving utilization coefficients of 1.0939 according to Rahimi and Maghrebi (2022). The implementation of hybrid optimization methods proves that joining multiple optimization methods produces better results for modern rebar cutting applications in construction. Table 2.2 compares the real-world applications of above-mentioned algorithms in commercial businesses. These tools

typically achieve Return on Investment (ROI) within 3-6 months through material savings alone (Widjaja et al., 2023).

Table 2.2. The comparison of real-world applications of the algorithms

| Software | Algorithm | Waste reduction | Processing speed | Reference |
|------------------|------------------|------------------------|-------------------------|---------------------------|
| Autodesk Revit | GA-BFD Hybrid | 18-22% | 150 rows/sec | (Wang, 2024) |
| Tekla Structures | LP-FFD | 15-18% | 80 rows/sec | (Rahimi & Maghrebi, 2022) |
| OptiCut Pro | Modified GA | 20-24% | 200 rows/sec | (Widjaja, 2023) |

3. Methodology

3.1. Research design

The capstone project was designed based on a mixed-methods approach using both quantitative and qualitative methods. The aim is to identify the underlying causes of material waste for Company A, quantify its financial impact, and create practical rebar cutting optimization software. The capstone project methodology consists of six distinct phases. First of all, the problem is identified using quantitative analysis in the form of a survey to gather statistical data on waste patterns, causes, and financial impacts; followed by qualitative insights gathered as an expert interview, with the head of the strategy department of Company A, to understand current waste management practices. Secondly, in the data collection phase, primary data on rebar characteristics, including mass, length, and quantity for several projects were obtained. During the third phase of algorithm development, mathematical modeling was formulated for the rebar cutting optimization as a one-dimensional cutting stock problem. The algorithm was developed using the Python programming language. The fourth phase of the methodology was the development of interfaces for users to more easily interact with the developed Python code of the optimization of rebar cutting. User interface allows stakeholders to upload files with requirements of the rebar usage calculations for a project and ensures seamless integration between the user interface and optimization backend. The fifth phase followed was validation and testing, consisting of a case study analysis to apply the developed digital tool to a real-world project from Company A. At this stage, the performance of the tool was compared and assessed with traditionally used methods. Additionally, a post-implementation survey was conducted to collect feedback on usability, effectiveness assessment of the proposed digital tool, also clarifying if there are any suggestions and/or areas for improvement. Finally, it is worth noting that ethical considerations were prioritized during all phases of the development of the capstone project ensuring confidentiality, consent in data collection, and transparency during the algorithm development. By combining empirical data with advanced modeling techniques, this capstone project offers a computational approach to optimizing rebar waste management for Company A.

3.2. Primary data collection

3.2.1. Primary data

Company A provided an Excel spreadsheet that contains rebar requirements for three construction projects. The dataset includes the length, quantity, and diameter of rebar required for the construction site. Table 3.1 presents a *sample of the data* extracted from the spreadsheet. This dataset is used in Python code to optimize rebar waste.

Table 3.1. Sample of data gathered from Company A

| Length (m) | Quantity | Diameter (mm) |
|------------|----------|---------------|
| 11 700 | 44 | 14 |
| 4 240 | 44 | 14 |
| 11 700 | 56 | 14 |
| 2 235 | 44 | 12 |
| 5 760 | 152 | 20 |

3.2.2. Survey

The first survey was developed in accordance with a questionnaire from the Joint Research Centre (JRC) of the European Commission, titled “Techno-economic and environmental assessment of construction and demolition waste management.” (García et al., 2024). The survey’s respondent was head of department, directly involved in construction planning and material procurement. The survey questions are provided in Appendix A. The survey included 26 questions, categorized as follows:

- 10 single-select multiple-choice questions. These questions were designed to gather specific quantitative data, such as company type, classification, industry, willingness to share information, and existing optimization measures.

- 7 multiple-select multiple-choice questions. These questions allowed the respondent to select multiple applicable responses, providing a broader perspective on factors contributing to waste generation and consequences in terms of financial losses.
- 9 open-ended questions. These questions were designed to capture qualitative insights, allowing respondents to elaborate on waste proportions, and potential improvements.

A structured *post-implementation survey* was designed to assess the effectiveness of the rebar waste optimization software after deployment (Appendix B). The purpose of this survey was to collect detailed user feedback on various performance dimensions of the software, including waste amount, cost savings, and time. The survey was distributed electronically to the site engineer involved in rebar procurement and cutting processes. To ensure ethical standards, participation was voluntary, anonymous, and based on informed consent.

There were five sections in the survey:

- General information collected optional respondent details (position, project) and duration of software use to contextualize responses.
- Time savings compared pre- and post-software time spent on rebar cutting plans and measured perceived efficiency improvements.
- Cost savings identified whether cost reductions occurred and estimated percentage savings in rebar procurement.
- Waste reduction part quantified waste reduction percentages and amount in tonnes.
- Features and suggestions ranked the most useful features, gathered open-ended feedback for improvements, and measured likelihood of recommending the software.

3.2.3. Expert interview

A semi-structured interview was conducted with the head of department to learn more about how rebar waste is managed on construction sites. The participant was selected based on the direct involvement in construction site operations, ensuring firsthand knowledge of rebar waste management practices. With a particular focus on the cutting process, the interview aimed to explore current procedures, challenges and possible solutions regarding waste management. Since the interviews were qualitative in nature, open-ended questions allowed for in-depth opinions and experiences to be collected. The questions included both quantitative and qualitative aspects such

as waste levels, schedule shifts, operational and financial impacts and possible optimization methods.

In total, the interview took 90 minutes, and consisted of 16 questions, devoted to the following sections:

1. General overview of rebar waste management;
2. Quantitative aspects of rebar waste;
3. Contributing factors for waste generation;
4. Financial and operational impact;
5. Time and scheduling impacts;
6. Optimization challenges;
7. Interest in optimization tools;
8. Feedback and additional insights.

3.3. Mathematical modeling of the algorithm for rebar cutting optimization

3.3.1. Problem description

The optimization problem of rebar cutting can be defined as follows: The standard length of a rebar is 11.7 meters. To meet structural specifications, rebars must be cut into specific lengths, referred to as *segments*. The remaining portion of the rebar after cutting is known as the *used rebar*.

Sets and Indices

- D - Set of all rebar diameters, indexed by d .
- S_d - Set of required segments for diameter d , indexed by s , where each segment has:
 - $l_{d,s}$ - Length (mm)
 - $q_{d,s}$ - Required quantity
- R_d - Set of used rebars for diameter d , indexed by r , where each rebar has:
 - l - Standard rebar length (11,700 mm)
 - d - Diameter (mm)
- ρ - Density of a rebar (7850 kg/m³)

Decision Variables

- $x_{d,r,s}$ - Binary variable indicating whether segment s is assigned to rebar r

- $x_{d,r,s} = 1$ if segment s is assigned to rebar r , 0 otherwise
- $y_{d,r}$ - Binary variable indicating whether rebar r is used
 - $y_{d,r} = 1$ if rebar r is used, 0 otherwise
- η - Utilization coefficient

3.3.2. Mathematical model

The goal is to minimize the total waste across all rebars:

$$\min_{L \in \mathbb{R}^{S_d \times D}} \sum_{d \in D} \sum_{r \in R_d} (l - \sum_{s \in S_d} l_{d,s} \cdot x_{d,r,s}) \cdot y_{d,r} \quad (3.1)$$

s.t.

L is a matrix:

$$L = \begin{bmatrix} l_{1,1} & \cdots & l_{1,s} \\ \vdots & \ddots & \vdots \\ l_{d,1} & \cdots & l_{d,s} \end{bmatrix} \quad (3.2)$$

Segment length constraint:

$$\sum_{r \in R_d} x_{d,r,s} = q_{d,s}, \forall d \in D, \forall s \in S_d \quad (3.3)$$

Rod capacity constraint:

$$\sum_{s \in S_d} l_{d,s} \cdot x_{d,r,s} \leq l, \forall d \in D, \forall r \in R_d \quad (3.4)$$

Rod usage constraint:

$$x_{d,r,s} \leq y_{d,r}, \forall d \in D, \forall r \in R_d, \forall s \in S_d \quad (3.5)$$

Binary variable constraint:

$$x_{d,r,s} \in \{0, 1\}, \forall d \in D, \forall r \in R_d, \forall s \in S_d \quad (3.6)$$

$$y_{d,r} \in \{0, 1\}, \forall d \in D, \forall r \in R_d \quad (3.7)$$

The following constraints are directed to ensure optimal and feasible solutions. The segment assignment constraint ensures that each required segment is produced exactly the specified number of times by summing the binary assignments $x_{d,r,s}$ across all rebars. The rod capacity constraint prevents the total length of segments in any rod from exceeding the standard rod length $l_{d,s}$ ensuring physical feasibility. The rod usage constraint links the assignment variables $x_{d,r,s}$ to the rod usage variables $y_{d,r}$, ensuring that waste is only calculated for rods that are actually used. Finally, the binary variable constraints enforce the discrete nature of the problem, ensuring that segments are either fully assigned to a rod or not, and rods are either used or not.

3.3.3. Additional calculations

The utilization coefficient measures the efficiency of material usage and is defined as:

$$\eta = \frac{M_{used}}{M_{required}} \quad (3.8)$$

$\eta = 1$: Perfect efficiency (no waste)

$\eta > 1$: Overuse (waste or inefficiency)

$\eta < 1$: Underuse (unused capacity)

where:

$$M_{required} = \sum_{s \in S_d} q_{d,s} \cdot l_{d,s} \cdot 10^{-9} \cdot \frac{\rho \pi d^2}{4} \quad (3.9)$$

$$M_{used} = \sum_{r \in R_d} y_{d,r} \cdot l \cdot 10^{-9} \cdot \frac{\rho \pi d^2}{4} \quad (3.10)$$

3.4. Web application development

The user-friendly web application of the rebar cutting optimization algorithm was developed in order to make it more accessible, scalable, and practical for convenient use in the construction industry. It consists of two main parts: the frontend dealing with user interaction and displaying, and the backend for processing data, executing algorithms, and storing files.

3.4.1. Frontend: User interface

To develop the application interface, HTML, CSS, and JavaScript are used, in which each has its own role. For example, HTML defines a web page in terms of structure and content, CSS in terms of visual presentation, and JavaScript in terms of interactivity and dynamic behavior (Glotzbach, 2024). The main goal to be achieved by the frontend of the developed solution is to create a user-friendly interface for the users to be able to upload data, start the optimization process, see the results and download reports. The followings are the key elements of frontend:

File uploading is the first key element of the frontend. An `<input type="file">` element in HTML, in other words, an input field allows users to select and upload a file containing the required rebar cutting information. The file selection event is handled using JavaScript and data is prepared to send to the backend.

Next frontend function is analysis initiation. There is an “Analyze” button that initiates the start of the optimization algorithm. When clicked, it sends the request to the backend via a JavaScript AJAX (Asynchronous JavaScript and XML).

The optimization process takes time, and to keep users informed about the current progress, a progress bar is dynamically updated by the frontend. To achieve this, the backend streams updates using JavaScript, which the frontend receives to adjust the width of the progress bar element. Once the analysis is done, the frontend will present the report in a results element. The results, such as waste calculations, cutting patterns, and overall utilization statistics, are presented in a readable, user-friendly format.

Lastly, for users who want to save the displayed results, a download button is available. This button is linked to the downloading endpoint on the backend, pressing which will get a file with the formatted results.

3.4.2. Backend: Algorithm execution

While the frontend processes what the user sees, all the heavy tasks are performed on the backend. The application’s backend is built with Python and Flask framework (Grinberg, 2014). Flask is a lightweight web framework which offers the tools and libraries required to create web applications. Backend will get data from the frontend, process it, run the optimization algorithm, and return the result to the frontend. The followings are the key elements of backend:

The first key element of the backend is data reception and processing. The endpoint to handle analysis receives the uploaded file from the frontend and accesses it through Flask's request object, after which it temporarily saves the file on the server. The file is then read and parsed using the Python module, in which the data is broken into segments of length, quantity, and diameter. Then, this data is used as input in the optimization algorithm.

The main component of the backend is the genetic algorithm, previously described in the sections above, which is implemented in Python and designed to cut the rods in a way that minimizes waste. During this process, the backend sends out progress updates via Flask's streaming capability to the frontend. This enables the frontend to show the progress bar dynamically. Once the algorithm is finished, the backend will create the result as a text string. Then they are saved to a text file in a designated results folder on the server. This file can then be downloaded by the user via the dedicated endpoint.

The communication between the frontend and backend takes place over HTTP. The frontend makes POST requests to upload data and start analysis; and the backend sends back real time info and the results.

3.4.3. Web application setup

To properly set up and open the web application, it is necessary to install the required dependencies, create the necessary directories, prepare the frontend and input files, and finally run and access the application.

The first step in setting up the application is to install the required Python packages. This can be done using pip, the standard package manager for Python. Specifically, two packages are needed: Flask, which serves as the backend web framework, and pyngrok, a library that allows secure internet access to the locally hosted application. In Python, this can be done using pip, the standard package manager. In particular, there are two packages: Flask, the backend web framework, and pyngrok, a library that allows secure access to the application through the locally hosted application. After installation of the packages, ngrok needs to be authorized with an authentication token. This will allow the use of pyngrok's tunneling features.

When the environment is ready, necessary directories such as templates, uploads and results should be created. The frontend HTML files will be stored in the templates folder, user submitted files will reside in the uploads folder, and reports generated will go to the results folder.

The application is ready to launch once all preparations are complete. When the Python script executes, it prints a URL to the console. This ngrok-provided URL can be used to access the application from any web browser.

3.5. Ethical considerations

During the process, ethical aspects were prioritized to ensure its reliability and protect the rights of both the company and the participants of the survey and interview. To maintain confidentiality, all responses were processed without specifying names, company names or any project details. Participation in the study was completely voluntary. All responses were provided in Russian. Before the survey, each participant was clearly informed that their feedback would be used exclusively for the capstone project, and all data for software generation.

4. Results and Discussion

4.1. Survey and interview results

Construction waste is a recurring issue, according to the survey and interviews. The predominant waste categories include concrete, bricks, tiles, cement and ceramics, followed by insulation materials and metal waste such as rebar. The survey results show that rebar waste accounts for about 25% of the total material used. Concrete, bricks, tiles and ceramics account for about 10% of the total construction waste, while insulation and metal waste account for 5% each. The waste volume is significant: 1,000 tonnes of concrete and ceramic waste, 150 tonnes of insulation materials and 30 tonnes of rebar waste.

Much of the waste is due to inefficient cutting of rebar. Workers mainly cut rebar manually, supplemented by semi-automated tools such as Excel calculations, which takes 24 hours (3 working days). However, inconsistent cutting methods and varying skill levels of workers result in significant material wastage. Waste levels are particularly high on complex projects where precision is more important but more difficult to maintain. Figure 4.1 illustratively explains the origin of the waste produced in the example of one rebar, being split into several cuts of different lengths due to project requirements.

Financially, waste has a significant impact on a company's budget. The respondent listed higher procurement costs, storage costs, and longer project times as the main consequences of poor waste management. In particular, concrete waste has historically led to budget overruns; rebar waste has often changed finances due to excessive procurement costs. Current waste management methods mainly involve changing cutting patterns and storing additional material for possible use. However, these strategies do not fully address the root causes of the problem, and material loss continues to be a problem, especially on large-scale projects, as worker skill levels and cutting methods are not aligned. To improve productivity and reduce material waste, the interviewee expressed interest in applying technology solutions such as real-time cost analysis systems and automated cutting optimization tools.

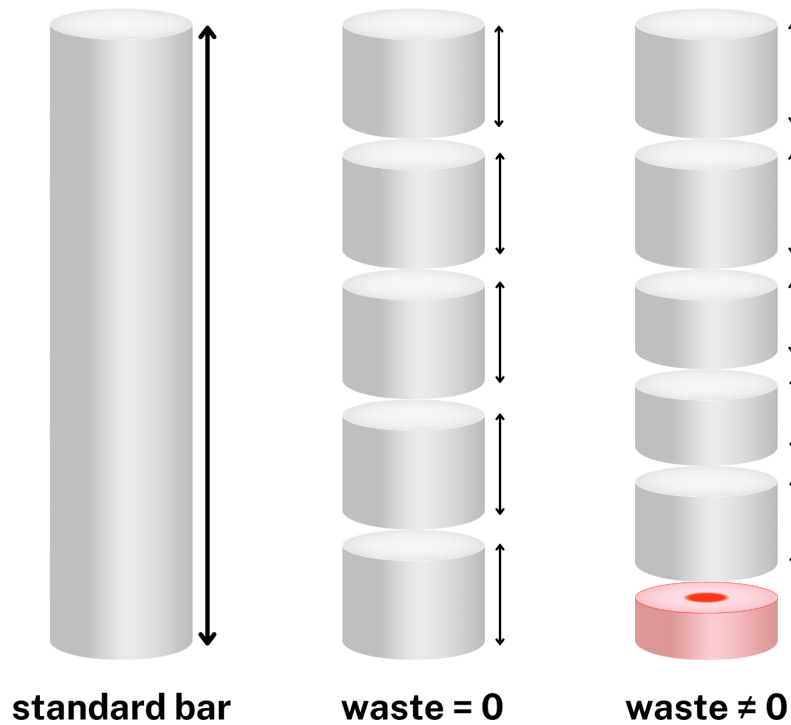


Figure 4.1. Illustration of number of cuts of rebar and waste generation

4.2. Algorithm for rebar cutting optimization

The rebar cutting stock process requires optimization of material waste reduction from standard 11.7 m rebars by dividing them into project-based required segments. The optimization method known as Genetic Algorithms (GAs) depends on natural selection principles for their design. The application of GAs proves effective when dealing with combinatorial optimization problems particularly in the context of rebar cutting. Earlier implemented greedy algorithm's flowchart is given in Appendix C, however, its efficiency was much lower in comparison to GA, thus, the second was selected for waste minimization in this project.

The search process in GAs maintains a balance between detecting fresh solutions (exploration) and improving existing beneficial solutions (exploitation). GAs maintain efficient operations for vast solution areas which prevents the excessive expense of using exact methods. GAs resolve various constraints using adjustable fitness functions that function in tandem with

adaptable constraints. The GA directs continuous population evolution using candidate solutions for cutting patterns through successive generational cycles. Key components include:

1. Initialization

A population of solutions is created, where each solution represents a set of cutting patterns.

```
FUNCTION InitializePopulation(segments, population_size):
    population = []
    FOR i = 1 TO population_size:
        solution = Randomly assign segments to rods without exceeding standard length
        population.append(solution)
    RETURN population
```

The function generates the first solutions that compose the population. A possible method to divide rebars into specified sections exists within each solution (individual). Random segment distributions to rods make up the initial stage before starting the algorithm but rod lengths stay under their prescribed standard. Biological evolution is reproduced by this step because the algorithm generates multiple solutions through random methods.

2. Fitness evaluation

The evaluation assigns points during scoring based on the total waste output. The lower the waste, the higher the fitness and suitability of the algorithm.

```
FUNCTION CalculateFitness(solution, standard_length):
    total_waste = 0
    FOR rod IN solution:
        used_length = SUM(segment.length IN rod)
        IF used_length > standard_length: RETURN -infinity // Penalize invalid solutions
        total_waste += (standard_length - used_length)
    RETURN -total_waste // Negative waste = higher fitness
```

The fitness function determines solution quality measurement. In this case, the scoring method uses total waste (unused rebar length) as its basis. The algorithm seeks efficiency through cutting pattern optimization because fitness increases when waste reaches lower levels. The algorithm receives penalties for solutions which contain rods longer than allowed standards.

3. Selection

The selection process for parents in reproduction employs tournament selection.

```
FUNCTION SelectParents(population, tournament_size):
    parents = []
    FOR i = 1 TO 2:
        candidates = Randomly sample tournament_size solutions
        best_candidate = Candidate with highest fitness
        parents.append(best_candidate)
    RETURN parents
```

4. Crossover

Two parents combine to create offspring. This implementation uses a segment shuffling.

```
FUNCTION Crossover(parent1, parent2, standard_length):
    combined_segments = [segments FROM parent1 AND parent2]
    Shuffle(combined_segments)
    offspring = Split shuffled segments into valid rods
    RETURN offspring
```

Crossover combines two parent solutions to create offspring. Segments from both parents are pooled and shuffled, then redistributed into new rods. This mimics genetic recombination in nature, where offspring inherit traits from both parents. The shuffling ensures exploration of new cutting patterns.

5. Mutation

Due to random changes such as interchange of rod segments the population stays diverse.

```
FUNCTION Mutate(solution, mutation_rate, standard_length):
    IF random() < mutation_rate:
        rod1, rod2 = Randomly select two rods
        segment1 = Randomly pick from rod1
        segment2 = Randomly pick from rod2
        SWAP(segment1, segment2)
        IF rods exceed standard_length: UNDO swap // Ensure validity
    RETURN solution
```

Following mutation, the solution will get small random modifications. Two different rod segments can be interchanged as an example of mutation implementation. The algorithm avoids being trapped in suboptimal solutions through population diversity principles.

6. Replacement

The population update method includes both high-performing solutions with new offspring produced through the process.

```
new_population = Top 5% of current population
WHILE new_population NOT full:
    parents = SelectParents(population)
    offspring = Crossover(parents)
    offspring = Mutate(offspring)
    new_population.append(offspring)
```

7. Global optimization

Post-optimal GA convergence occurs when a repacking operation handles segments with the goal of additional waste reduction.

```
FUNCTION GlobalOptimization(solution, standard_length):
    all_segments = Extract all segments from solution
    Sort segments by descending length
    new_solution = []
    current_rod = []
    remaining_length = standard_length

    FOR segment IN all_segments:
        IF segment fits IN remaining_length:
            ADD segment TO current_rod
            remaining_length -= segment.length
        ELSE:
            ADD current_rod TO new_solution
            RESET current_rod with segment
    RETURN new_solution
```

After the genetic algorithm achieves convergence, this step uses a best-fit decreasing approach to incorporate all segments into rod structures. The system selects longer segments first

in order to decrease space loss. The processing step verifies that further enhancements through simple arrangement modifications are impossible.

Figure 4.2 below depicts a flowchart of the GA's work, showing important decisions and steps needed for the algorithm to succeed as discussed above. The hybrid GA overall achieves the following results which indicate the effectiveness of the algorithm.

- 1. The method explores different slicing forms, which results in waste reduction when implemented on a global scale.
- 2. The system delivers its solutions only in a few minutes regardless of order size.
- 3. The design allows simple modifications based on changing specifications such as diameter-specific parameters.

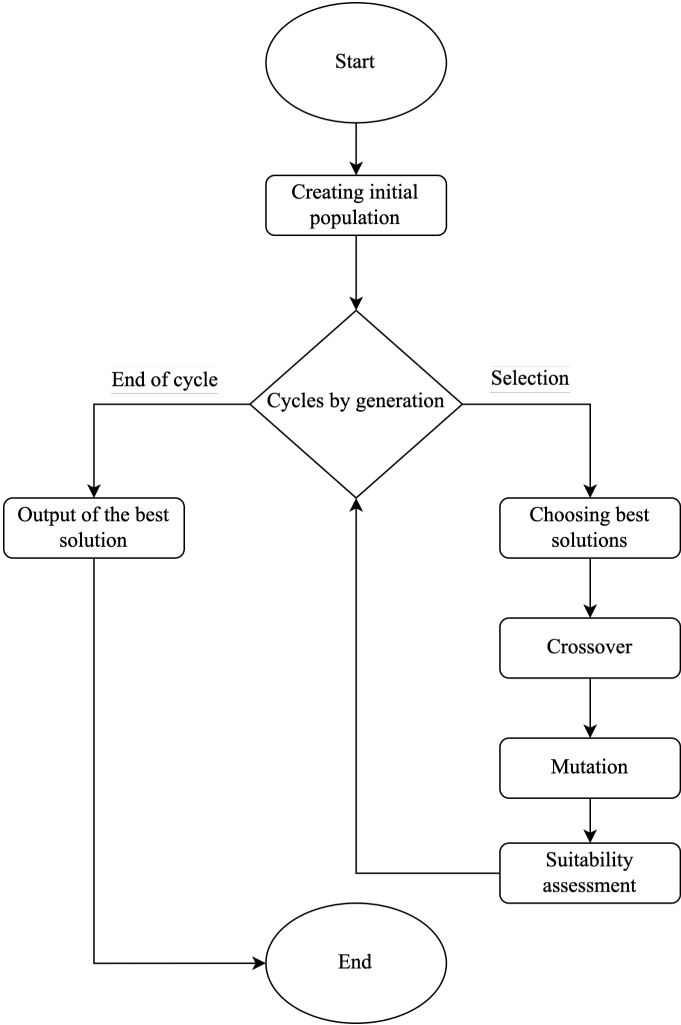


Figure 4.2. Genetic algorithm flowchart

4.3. Web application interaction

The web application, designed to deliver the outcomes of the rebar cutting optimization algorithm in a more practical and convenient way for peripherally involved users, was developed and successfully tested. It shows an interactive workflow between frontend and backend components. The interface of the web application at the beginning consists of two buttons and a results window as shown in Figure 4.3.

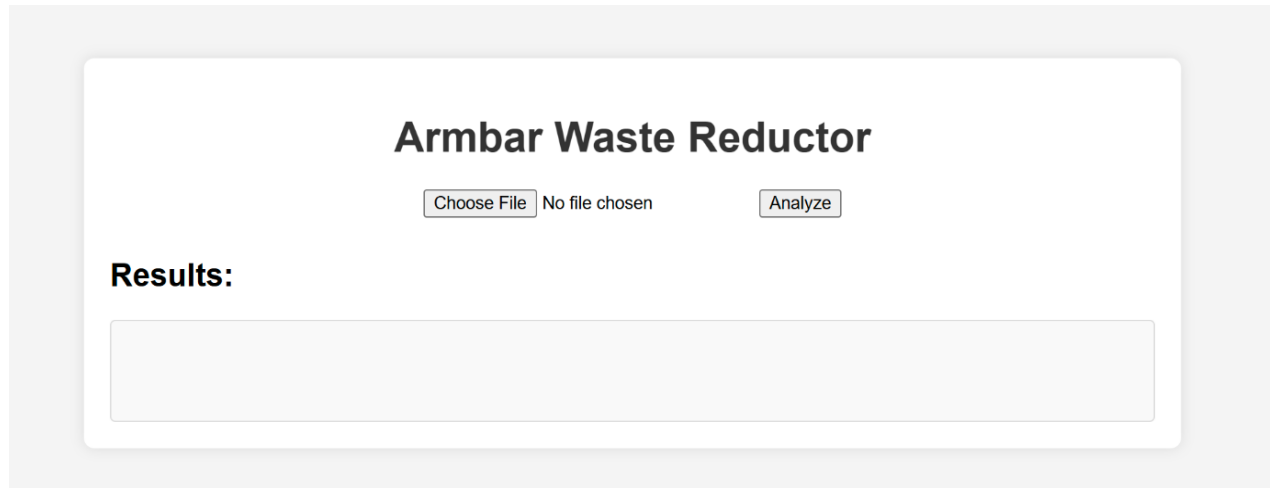


Figure 4.3. Initial interface

Pressing the 'Choose File' button allows the user to upload a file containing the required rebar cutting information. The 'Analyze' function only works after the file is received. Otherwise, a notification will appear prompting the user to select a file. When the 'Analyze' button is clicked, it launches the optimization algorithm. Simultaneously, a progress bar appears to display the real-time computation status (Figure 4.4).

Once the analysis is done, as shown in Figure 4.5, the digital tool generates a comprehensive report containing information about cutting patterns, waste reduction, and material usage in a result window.

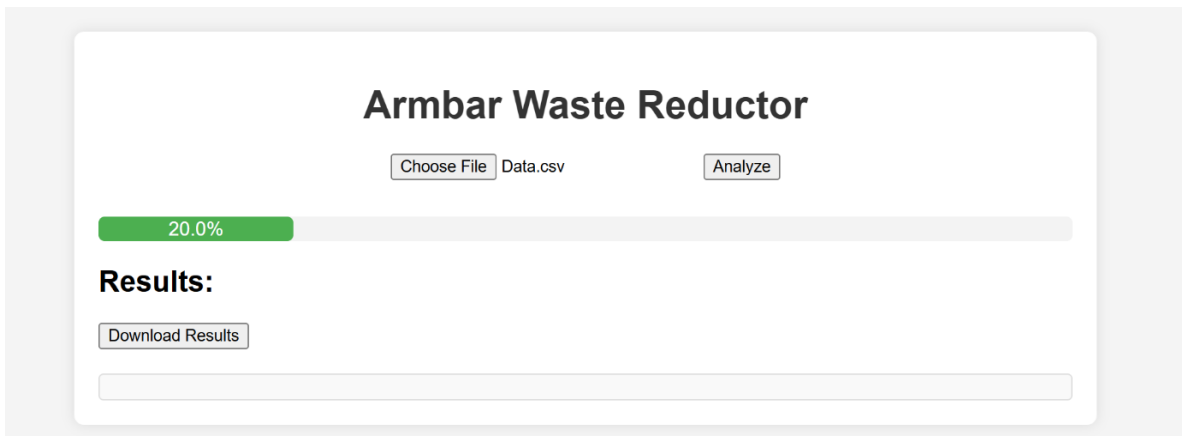


Figure 4.4. Interface during the optimization process

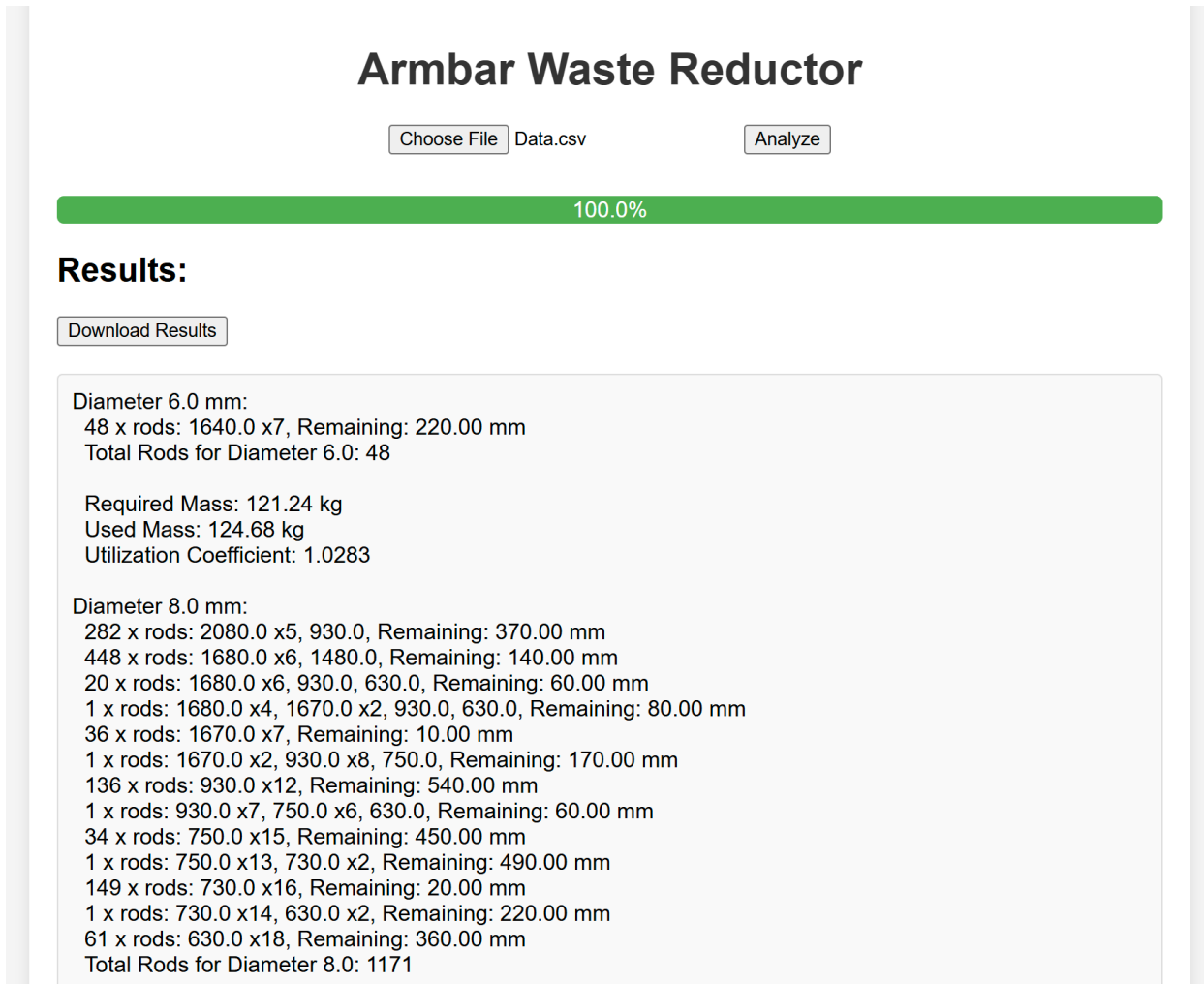
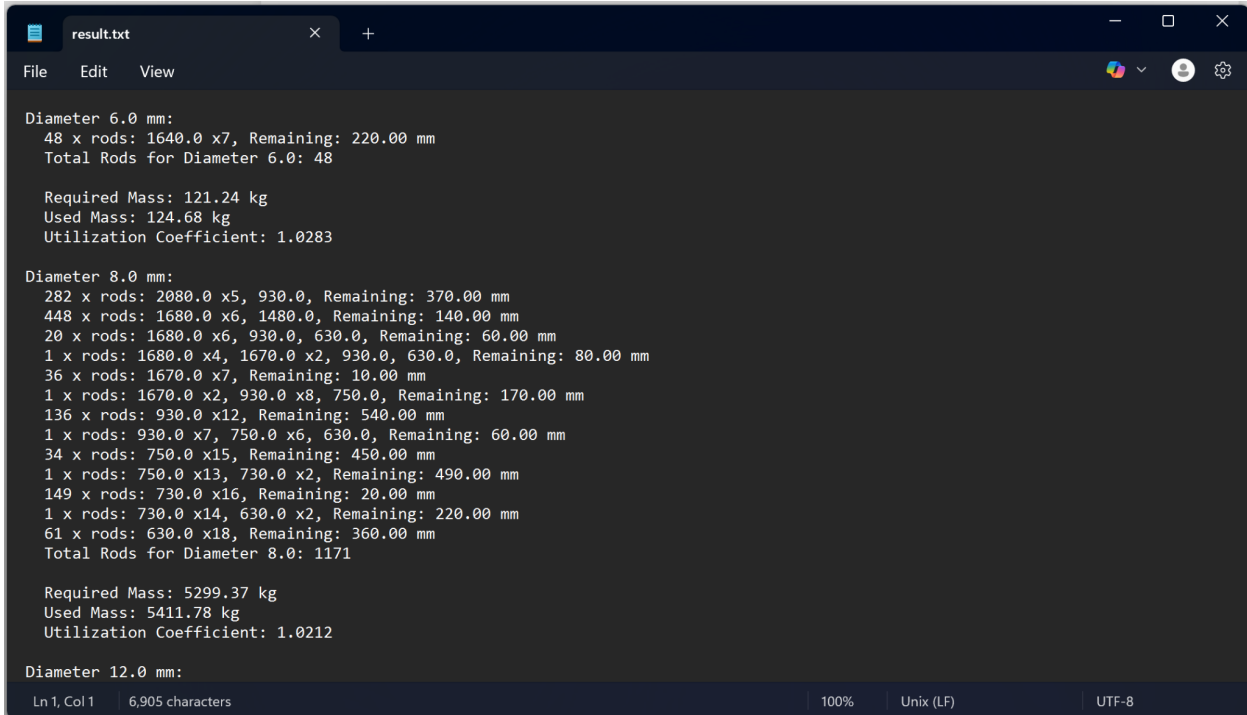


Figure 4.5. Final interface

There is also an option to download the displayed results by pressing the ‘Download Results’ button, which saves the data in a text file (Figure 4.6).



```
result.txt
File Edit View
Diameter 6.0 mm:
48 x rods: 1640.0 x7, Remaining: 220.00 mm
Total Rods for Diameter 6.0: 48

Required Mass: 121.24 kg
Used Mass: 124.68 kg
Utilization Coefficient: 1.0283

Diameter 8.0 mm:
282 x rods: 2080.0 x5, 930.0, Remaining: 370.00 mm
448 x rods: 1680.0 x6, 1480.0, Remaining: 140.00 mm
20 x rods: 1680.0 x6, 930.0, 630.0, Remaining: 60.00 mm
1 x rods: 1680.0 x4, 1670.0 x2, 930.0, 630.0, Remaining: 80.00 mm
36 x rods: 1670.0 x7, Remaining: 10.00 mm
1 x rods: 1670.0 x2, 930.0 x8, 750.0, Remaining: 170.00 mm
136 x rods: 930.0 x12, Remaining: 540.00 mm
1 x rods: 930.0 x7, 750.0 x6, 630.0, Remaining: 60.00 mm
34 x rods: 750.0 x15, Remaining: 450.00 mm
1 x rods: 750.0 x13, 730.0 x2, Remaining: 490.00 mm
149 x rods: 730.0 x16, Remaining: 20.00 mm
1 x rods: 730.0 x14, 630.0 x2, Remaining: 220.00 mm
61 x rods: 630.0 x18, Remaining: 360.00 mm
Total Rods for Diameter 8.0: 1171

Required Mass: 5299.37 kg
Used Mass: 5411.78 kg
Utilization Coefficient: 1.0212

Diameter 12.0 mm:
Ln 1, Col 1 6,905 characters 100% Unix (LF) UTF-8
```

Figure 4.6. Downloaded results file

4.4. Testing and feedback

To evaluate the effectiveness and operational impact of the rebar cutting optimization software, a post-implementation survey was conducted with the department director who transferred the software to the material planning and procurement unit. Based on our software, Company A used it on parts of three real construction projects: the construction of two residential complexes and a school. The comparison between manual calculations and the software output was made based on three key parameters: *calculation time*, *amount of rebar waste (in tonnes)*, and *cost savings (tenge)* which is shown in section 4.5.

4.4.1. Time efficiency

Before implementing the software, the team reported spending over 24 hours as indicated by surveys and interviews, which is equivalent to three full working days. During planning, a specialist prepared a cutting plan using manual Excel-based calculation method. In comparison,

the software processed over 25,000 individual rebar rows in 122 seconds, providing a high processing speed of approximately 209 rows per second. This means that the calculation time was reduced from 24 hours to 2 minutes. This test demonstrated the computational efficiency of the tool and its practical applicability to real-world operations on site. Survey responses also confirmed that the software significantly reduced the time required, i.e. the time required was reduced to 15 minutes, including processing time of software and verification of the software results by the specialist.

4.4.2. Waste amount

The results of waste reduction are summarized in Table 4.1. The amount of rebar needed for the construction project is specified as “Rebar required”. The company always orders 30% more rebar than calculated in manual calculations to reduce the risk of shortages or incorrect cutting. Therefore, this parameter is specified as “Rebar ordered”. A total of 559.3 tonnes of rebar were ordered within the three projects. The software solution does not include the ordered rebar parameter; therefore, it was assumed that the company would order 5% more rebar than the required amount according to the software calculations (Kim et al., 2004). It reduces the amount of rebar ordered to 507 tonnes, which means a reduction in the total purchase volume by 9.3%. This optimization is especially important from a financial point of view, since it directly leads to a reduction in the initial costs of purchasing material. Besides, the manual approach used 553.9 tonnes, while the software system used 482.9 tonnes, reflecting a 12.8% reduction in actual material usage. In both cases, the required amount of rebar of 430.2 tonnes was fully satisfied.

The total waste was divided into two categories: reusable and non-reusable waste. Reusable waste refers to rebar that was not used in the cutting process since the company orders more rebar than required. The company stores this type of waste for future use. Therefore, reusable waste is defined as the difference between the ordered and used material. This waste increased from 5.4 tonnes in the manual scenario to 24.1 tonnes in the optimized case. This shift indicates that the software was more efficient at consolidating usable offcuts that could be reused on-site or in future projects, rather than creating permanent waste. Non-reusable waste refers to rebar that was left over after improper cutting and cannot be used further and is discarded. In contrast, non-reusable waste decreased from 123.7 tonnes (manual) to 52.6 tonnes (software). This reduction represents a significant improvement in cutting accuracy and planning alignment.

Using the software, it was possible to reduce the total volume of waste, which is calculated as the difference between the ordered and required reinforcement bar, from 129.1 tonnes to 76.8 tonnes (t) compared to the manual approach. This reduction by 40.5% reduces the costs of storage, disposal and recycling of waste, and also has a positive effect on the environmental situation, which will be discussed in more detail in the following sections. In addition, the efficiency calculated as the ratio of the required rebar to the actually used one increased from 77.7% with manual calculation to 89.1% with the use of Python software. This increase of 14.7% demonstrates the significant potential of the program in optimizing the use of materials and minimizing waste.

Table 4.1. Waste amount comparison for manual calculation and software solution

| Metric | Manual Solution | Software Solution | Improvement |
|---|------------------------|--------------------------|--------------------|
| Rebar ordered (t) | 559.3 | 507.0 | 9.3% |
| Rebar used (t) | 553.9 | 482.9 | 12.8% |
| Rebar required (t) | 430.2 | 430.2 | - |
| Reusable waste (t) (ordered - used) | 5.4 | 24.1 | - |
| Non-reusable waste (t) (used - required) | 123.7 | 52.6 | - |
| Total waste (t) (ordered - required) | 129.1 | 76.8 | 40.5% |
| Efficiency (%) (required/used) | 77.7 | 89.1 | 14.7% |

4.5. Assessing financial impact

The economic advantages of using rebar cutting optimization software over conventional manual planning techniques were evaluated by financial comparison. Four main financial indicators: total procurement cost, cost of material used, cost of requirements (based on cost estimates of the necessary rebar quantities), and cost of ineffective material use formed the basis of the analysis. Table 4.2 compiles the results of financial impact analysis.

With the manual approach, the total procurement cost, which is the money spent on all the rebar ordered, was 167.8 million tenge, regardless of the efficiency of use. This value was reduced to 152.1 million tenge, a reduction of 15.7 million tenge, due to the software optimization. This reduction reflects more accurate procurement planning, which prevents over-ordering of rebar that would otherwise be wasted or unnecessary.

In addition, the cost of the materials used also clearly showed improvement. Manual planning resulted in a 166.2 million tenge total material cost; the software optimization lowered this to 144.9 million tenge, saving 12.8%. This emphasizes not only less material ordered but also more precise management of the used materials, so minimizing needless use during the cutting process. The base cost needed to satisfy the design needs of the project, or the cost of structural requirements remain constant at 129.1 million tenge since the required amount of rebar remains the same in both cases.

Nevertheless, the cost of ineffective material use, which was determined as the difference between the cost of materials ordered and the cost of rebar required—is the main indicator of the efficiency gains. Manual planning showed the material use cost of 38.7 million tenge; and with optimization software, the cost dropped to 23.0 million tenge. Therefore, 40.5% reduction in cutting process inefficiencies will lead to a reduction in financial costs associated with raw material waste.

All the above considered, financial analysis shows that the use of software is much more profitable than manual data processing. The use of this optimization tool on several projects will allow the company to save millions of tenge annually. Thus, investments in this software are highly effective and scalable, providing significant financial benefits for future construction projects. Thus, the automation of the process provided by the software not only reduces material costs, but

also allows for a significant increase in the company’s profit in the long term due to its application on many projects. Savings confirm the high return on investment in this program.

As a result, the use of optimization software will bring the following benefits to the business:

- Reduce the cost of rebar usage;
- Prioritize the allocation of funds for other construction needs instead of increasing funding for waste management;
- Increase the accuracy of budget planning and allocation.

Table 4.2. Financial comparison of manual and optimized solution for three projects

| Metric | Manual Solution | Software Solution | Reduction |
|--|------------------------|--------------------------|------------------|
| Total purchase cost (mln ₹) | 167.8 | 152.1 | 15.7 |
| Used material cost (mln ₹) | 166.2 | 144.9 | 21.3 |
| Structural requirement cost (mln ₹) | 129.1 | 129.1 | - |
| Cost of inefficient material use (mln ₹) | 38.7 | 23.0 | 15.7 |

4.6. Assessing environmental impact

Reducing construction waste is an important step towards improving the environment. Steel production and recycling are very resource and energy-intensive. Research shows that recycling one tonne of construction waste can prevent up to 264 kg of CO₂ emissions (Caro et al., 2023). Thus, knowing the amount of rebar waste avoided in a project helps to calculate how much CO₂ was saved using emissions per tonne of recycled CDW.

$$\begin{aligned}\text{CO}_2 \text{ savings} &= (129.1 \text{ tonnes} - 76.8 \text{ tonnes}) \times 264 \text{ kg CO}_2/\text{tonne} = 13,807.2 \text{ CO}_2 \\ &= 13.8 \text{ tonnes of CO}_2\end{aligned}$$

Apart from the notable increase in financial performance, the solution reduced CO₂ emissions by 13.8 tonnes. This achievement is directly related to the optimization of rebar use. The software significantly reduced the volumes of rebar used, ordered and discarded. Such a significant reduction in rebar use has environmental implications. Reducing its use through software is equivalent to reducing the emissions from driving several cars for an entire year, and this is just one aspect of the positive impact on the environment. The implementation of the software was an important step towards the transition to a circular economy in the construction industry. In this way, the company can demonstrate its commitment to the principles of sustainable development. This has a positive effect on the company's image and contributes to an increase in its corporate social responsibility (CSR) rating. Investors are increasingly paying attention to the environmental component of enterprises, and this optimization is a shining example of a responsible approach to business, attracting investment and strengthening the company's reputation. As a result, the company receives a double win: improved financial results and a contribution to preserving the environment.

4.7. Case study

The case study in this section explicitly shows the effectiveness of the solution proposed in this capstone project in the example of the school construction project completed by Company A in Astana. The project utilized rebars throughout the entire project for structural components starting from foundations up to columns, beams and slabs. The project specifications required builders to construct two floors on 2,500 square meter building grounds; and the structural design required rebar elements of multiple diameters. Table 4.3 demonstrates the range of rebars' diameters along with their masses purchased for the project execution. The total mass of rebars purchased is equal to 162.1 tonnes of reinforced steel bar.

Out of the total rebar ordered, 147.7 tonnes were used in construction, although only 124.7 tonnes were actually required to complete the project. This left 37.4 tonnes unaccounted for, of which 14.4 tonnes remained unused. A portion of the remaining 23 tonnes would have been

unavoidably wasted; however, due to inefficient cutting practices, this amount was significantly increased.

Table 4.3. The construction team purchase of rebars of different diameters for manual solution

| Diameter (mm) | 6 | 8 | 12 | 14 | 16 | 18 | 20 | 22 | 25 | 28 |
|--------------------------|-----|------|------|------|-------|-------|-------|------|-------|------|
| Mass (kg) | 200 | 6900 | 2200 | 4600 | 16400 | 28700 | 84400 | 3700 | 11200 | 3800 |

The construction team managed the cutting of rebar manually and followed standard cutting practices based on structural requirements. However, the cutting was not optimized for minimizing waste, as the workers on the construction team mostly relied on their experience and logic. The result was several offcuts from a few kilograms to large excess pieces. The main factors of inefficiencies were the lack of a structured way to optimize rebar cuts, human errors in measurement and cutting, and overestimation when ordering materials resulting in excess stock. As a result, only 76.9% percent of the ordered rebar was effectively utilized, 23.1% was wasted, of which 8.9% were unused surpluses. Figure 4.7 illustrates a possible cutting plan depending on project requirements made by site engineers for the rods with diameter of 14 mm. It is worth to note that this scheme is proposed as engineers usually use the strategies like 1) cutting the biggest segments first; 2) separately grouping similar lengths; and combining small pieces with big ones is usually not practiced.

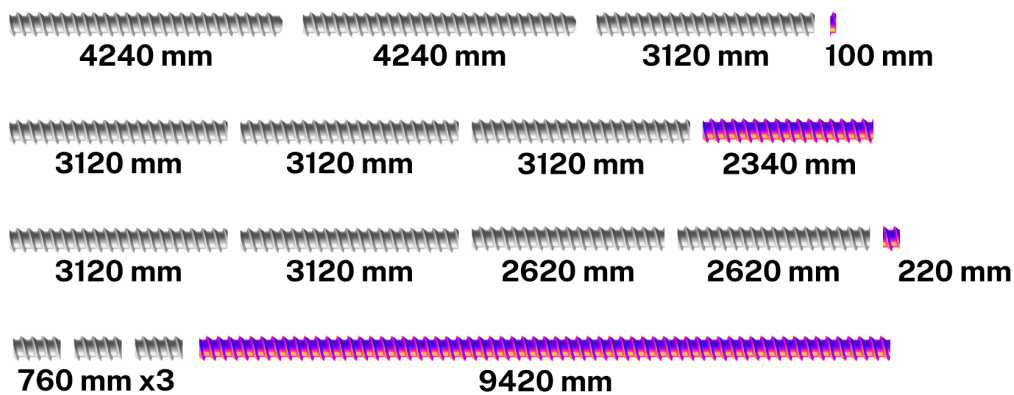


Figure 4.7. Example of manual (inefficient) cutting plan for the rods with $d = 14$ mm

The developed optimization tool was applied in order to test how much waste could have been reduced for the same project. The solution analyzed the required lengths, determined the most efficient cutting patterns, and optimized the cutting patterns to minimize waste. Strategic pairing cuts were made to minimize waste, and offcuts were reduced to almost negligible size, with significant material efficiency. Given that the project required 124.7 tonnes of rebar, the project would have inevitably used only 136.4 tonnes of rebar, 7.6% less than the manual approach. Thus, the construction team can place fewer rebar orders by improving planning. For this case study it would approximate to 143.2 tonnes with the assumption that the company would order 5% more rebar than the required (Kim et al., 2004). Figure 4.8 illustrates a sample of the efficient cutting plan calculated using the digital tool for the rods with $d = 14$ mm according to the requirements of this case study. Also, Table 4.4 compares the results of both manual and optimized solutions for the case study and specifies the improvement which could have been made if the digital optimization tool was used for this particular project.

Table 4.4. Comparison of manual and optimized solutions for the case study

| Metric | Manual Solution | Software Solution | Improvement |
|---|------------------------|--------------------------|--------------------|
| Rebar ordered (t) | 162.1 | 143.2 | +11.7% |
| Rebar used (t) | 147.7 | 136.4 | +7.6% |
| Rebar required (t) | 124.7 | 124.7 | — |
| Total waste (t) (ordered - required) | 37.4 | 18.5 | +50.5% |
| Efficiency (%) (required/used) | 84.4% | 91.4% | +7.0% |

After the comparison of two approaches, the manual cutting process was found to be very inefficient. In contrast, utilization increased, while the material waste was reduced dramatically by

the optimized method. It would have also reduced the waste in disposal costs and environmental impact. Furthermore, the optimized cutting approach would have made the work on site less labor intensive and less prone to error.

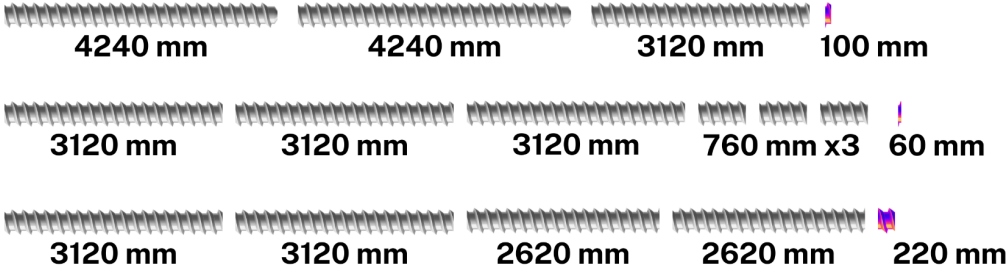


Figure 4.8. The efficient cutting plan made using the digital tool for the rods with $d = 14$ mm

The case study demonstrated how digital solutions can greatly increase the efficiency of construction management. The use of the developed rebar cutting optimization solution can reduce the total waste over 50% compared to manual methods which also results in significant cost savings. This method can be replicated easily in other construction projects, which makes this a useful tool for companies seeking to enhance material efficiency and cost control.

5. Engineering management using Lean Digital Construction

Lean principle is based on reduction of waste (Nikakhtar, 2015). The automating of rebar layout and minimization of its use leads to decrease in over-processing and material waste. Using Building Information Modeling (BIM) based rebar cutting estimations aligns with digital transformation strategies and enhances workflow efficiency as well as minimizes manual intervention following the principles of Lean Continuous Improvement (Wang, 2024).

According to research results, lean principles such as Just-in-Time (JIT) delivery, Value Stream Mapping (VSM), Last Planner System (LPS) can be and are recommended to be implemented in the Kazakhstani construction sector.

Briefly, *Just-in-time (JIT) delivery* is one of the suitable principles of Lean Construction Management for minimizing material holding. The JIT delivery approach seeks to provide materials exactly when they are needed on construction sites, thus minimizing inventory durations and avoiding overstocking. This is especially important for rebar optimization under limited storage conditions because rebar is bulky, has specific stacking requirements, and must often be carefully handled to avoid material degradation (Gerber, 2010). The digital tool developed helps to implement the JIT delivery for construction companies by delivering data-driven insights to procurement teams, using which, they can order rebars based on the needed amount for projects. Even so, as over-ordering is a regular practice in the construction sector, it was assumed a five percent over-ordering rate for Company A by analyzing the estimations of ordering rebars by Kim et al. (2004). This value can be adjusted depending on the company regulations for other players of the industry.

Value stream mapping (VSM) is a tool to visualize the flow of materials, information, and tasks required to deliver a product or service (Tyagi, 2015). The key idea is to identify and eliminate waste - activities which do not add value to the processes in rebar procurement and installation. In the scope of this work, VSM can be applied to map the end-to-end process of ordering rebar, delivering, and on-site installation for Company A. Using the VSM, Company A can identify the presence and/or absence of such bottlenecks like delays in approvals, inaccurate demand forecasts, inefficient material handling (Li & Solís, 2018; Setiawan et al., 2021). In this report, VSM principles are applied, though, not mapped due to insufficient data, thus, recommended for Company A to apply into operations to allow stakeholders visualize the real-

time data flows across departments for construction, macro and construction support processes as identified by Li and Solís (2018). The work of Vilventhan et al. (2019) can be a vivid example of implementing VSM to identify and assess material waste in construction.

Last planner system (LPS) is a framework to help to manage scheduling and coordination between design, procurement, and construction teams (Heigermoser, 2019). This is a planning system involving all project stakeholders to create a realistic schedule to ensure that each step in construction is coordinated accordingly. During recent times, this management approach is becoming increasingly popular owing to its design based on improved collaboration and communication among all stakeholders involved in a construction project. According to the Lean Construction Institute, reducing the trade inconsistency, time period between commitment to accomplishment and actual completion of work, from 50% to 25% can decrease the risk of project delays by a factor of six, which implies the significant impact of LPS on project timelines (Digital, 2023). Core components of LPS include master scheduling (outlining major milestones aligning all stakeholders), phase scheduling (determining task sequences and durations for each milestone), lookahead planning (identifying and resolving constraints in advance), weekly work planning (committing to tasks a week before), and a learning phase which is important for fostering continuous improvement and real-time adjustments (Digital, 2023). In the work of Buitrago (2016), when comparing the construction projects, 5% cost overruns were observed for the one without implementation of LPS, while implementation of LPS using the earned value management as a key metric showed 7% of budget savings. This might imply that when LPS's components are mastered collectively, the productivity enhancement, waste reduction and improved workflow could maximize the value in construction projects.

Except for the Lean Construction Management tools discussed, there are other tools and frameworks for project management and decision support systems which help to optimize resource allocation, manual errors and establish a structured system. This section discusses the combination of Lean Digital Construction systems with BIM in order to enhance stakeholder collaboration and workflow simplification.

5.1. Strategic integration plan

As stated at the beginning of the work, one of the main deliverables of this capstone project is to propose a guideline according to which the implementation of the algorithm on rebar cutting optimization into Company A's operations could be easier. Section 4 shows that the tool along with its algorithm and mathematical modeling has been developed and tested on three projects, also exemplified by a case study project all of which were delivered by Company A. However, this does not yet mean the adoption of the tool by construction companies, for this reason the next step is a structured deployment of the rebar cutting optimization tool that maximizes its benefits. Similar to the benefits shown in subsections 4.4-4.7 for Company A projects, the literature review results also support the adoption and implementation of digital technologies in lean construction to achieve greater economic efficiency including itself an increased speed of construction through reducing time for inter-operational losses; reduced time and operating financial costs via accurate cost estimates; reduced number of clarifications and changes in the project; integrated management monitored in real-time; increased labor productivity; as well as improved quality of works as a result of continuous improvement (Uvarova et al., 2023; Chen et al., 2021; Simanjuntak, 2023). Following the Jahanger et al. (2022) and similar studies (Schnell et al., 2022; Wang et al., 2020), the integration proceeds in four key phases starting from an initial pilot to full institutionalization at the same time guided by ADKAR change management model in order to engage stakeholders at each step (Jaaron et al., 2021). As proposed, this strategic plan emphasizes lean and continuous improvement principles, and aligns with Company A's broader objectives of efficiency, sustainability, and digital transformation.

Phase 1: Pilot implementation

In Phase 1, the rebar cutting optimization tool is used on a small-scale construction project. The objective of this phase is to validate this tool in a real but low-risk project environment as well as gather initial feedback (Kalman, 2024). According to the ADKAR model also depicted in Figure 5.1, this phase is designed to increase awareness, announce changes and explain the reasons behind the change on a limited scale (Jaaron et al., 2021). The small-scale project can either be a single building or a section of a larger construction, where project engineers can use the algorithm to generate rebar cutting plans. Key stakeholders such as structural engineers, procurement staff, and

site managers should participate in the pilot in order to provide a 360° evaluation of the tool's performance and usability.

During this phase, key performance metrics such as the percentage reduction in rebar used, the volume of waste generated, the time taken to produce cutting plan, and overall ease of use must be gathered and analyzed in comparison to doing the same work without using the digitized tool (Rahimi & Maghrebi, 2022). Thus, the awareness of stakeholders is increased, they become more acknowledged with the current high levels of rebar waste, inefficiencies of manual cutting and unoptimized procurement planning. The implementation team could also show the alignment of this strategy with national policies to further increase the stakeholders' engagement.

Similar to pilot project, a case study has already been exemplified in subsection 4.7, however, it included simulation of the minimum number of stakeholders needed for the execution of the cutting plan part without engaging the whole team of stakeholders such as procurement officers, site engineers, and project managers, thus, the need for Phase 1 is crucial. According to the literature, using similar optimization algorithms, it was possible to achieve up to 17.76% reductions in total usage of rebar with less than one percent (0.83%) cutting waste (Widjaja et al., 2023). In our case, as shown above in the case study, the reduction of total waste is approximately 50.5%, while the cost savings based on rebar ordering are up to 11.7% for one project. The implementation of our algorithm for the project could have resulted in cost savings of approximately 5.7 million tenge. Thus, the pilot stage could confirm the benefits in Company A's context and uncover any practical issues. Feedback mechanisms are crucial from the start of a pilot to capture suggestions and/or problems in real time (Kalman, 2024). The end result of Phase 1 is aimed at gathering quantitative evidence of material savings and efficiency gains, as well as qualitative insights from users regarding the tool's strengths and weaknesses in the case of Company A.

Phase 2: Feedback loop and refinement

Phase 2 focuses on analyzing the outcomes of the pilot project and refining the solution before implementing a wider deployment. All feedback and performance data from the pilot project are systematically reviewed to identify pain points for further improvements. Such an iterative feedback loop is critical to enhance the tool's functionality and user-friendliness before

scaling up. At this step, the desire of the stakeholders should be enhanced by addressing the concerns, raising their willingness to change.

During the initial steps of the algorithm development, we, as a capstone team, have encountered such a problem when the greedy algorithm did not fully deliver the parameters and cutting plan as intended and efficiency was somewhat similar to manual calculation results with a bit more efficiency, thus, after testing and verification, we made refinements and at the final version came to a conclusion to choose a genetic algorithm. Thus, the final version of the algorithm already shows a good performance, probably the need for refinement might only occur regarding the adjustments based on cutting optimization rules or adding features to handle site-specific scenarios which could arise during the pilot project. Similarly, the user interface and integration points such as input, export formats might be addressed if any changes become necessary for example for procurement systems. Currently, the input and output formats implemented are .csv and .txt respectively, which are compatible with Company A’s current operating system.

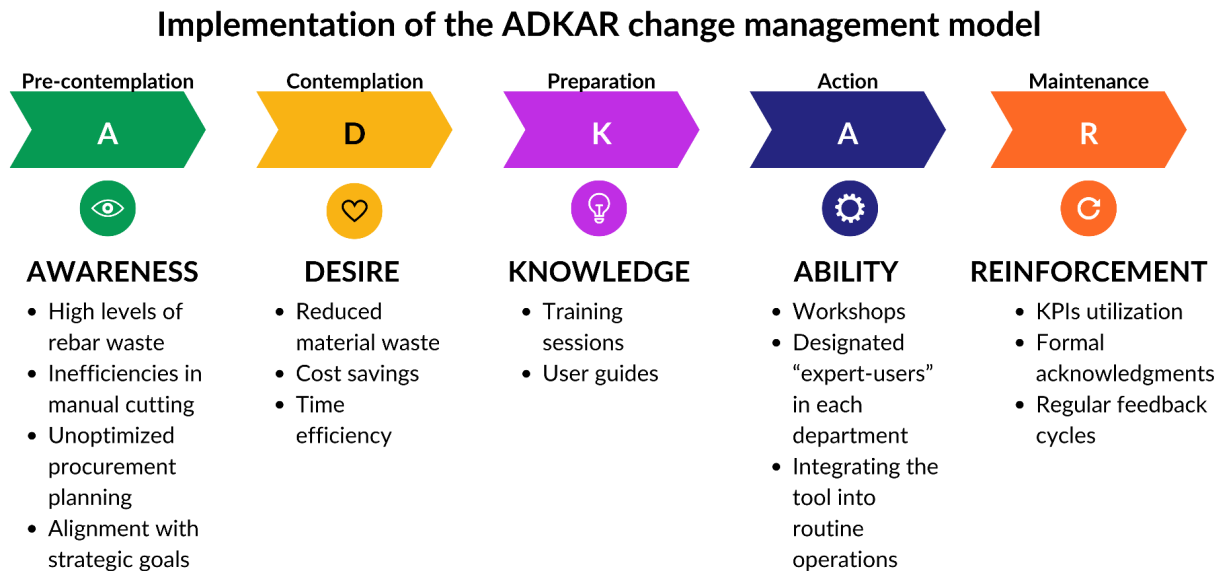


Figure 5.1. ADKAR change management model for the integration of the rebar cutting optimization tool into Company A’s operations

After gaining information on project performance, that can be used to enhance the desire of stakeholders in the forms of reduced material waste, significant cost savings as well as time

efficiency exemplified by a case study and literature review results (Rahimi & Maghrebi, 2022; Widjaja et al., 2023).

At this stage, the training materials and user guides (standard operating procedures) should be updated based on pilot learnings, making sure the clarity of how to use the tool effectively based on the ‘Knowledge’ aspect of the ADKAR model (Changwo, 2022). As discussed in Simanjuntak (2023), providing adequate knowledge and required skills hugely support and impact the effectiveness of the project implementation process.

By the end of Phase 2, the algorithm and its supporting materials are reconsidered and refined to be ready for a broader use. It is also worth mentioning that this stage embodies a continuous improvement: the implementation team iterates on the solution so that it better fits operational realities and user needs (Kalman, 2024). By sharing the pilot’s success data with Company A’s leadership and departments, skepticism related can be addressed and be set for company-wide adoption.

Phase 3: Department-wide deployment

In Phase 3, the optimized rebar cutting tool is to be deployed across relevant departments of Company A on a larger scale. Based on the successful pilot and refinements, the company launches the tool for cutting optimization of rebar to use in multiple projects simultaneously. It is suggested that the *target departments* should include:

- the structural design teams who state input rebar requirements into the tool;
- the procurement department members, who are responsible for ordering rebar stock based on the digital tool’s outputs;
- construction/site management teams, who oversee cutting and assembly on site using the optimized plans.

A structured training program should be executed to onboard all users in these groups. This, for example, involves hands-on workshops for engineers and site supervisors to become proficient with the algorithm’s interface and features. These measures follow the guidelines of the ‘Ability’ step according to the model and help to implement desired skills among stakeholders (Jaaron et al., 2021). In addition, dedicated sessions for procurement officers should be conducted

to integrate the tool's output with ordering and inventory processes to transit to a just-in-time procurement system aligning with lean digital construction management aimed to save resources (Jenewattananond, 2017). This could enhance utilization of the tool, integration and interoperability for the company stakeholders as highlighted in Leppänen (2024). IT support staff are trained to ensure that they can maintain the software, handle user accounts, and troubleshoot technical issues. Clear documentation in the form of user guides including FAQs (frequently asked questions) is provided to reinforce training and serve as ongoing reference (Moreo et al., 2012).

During the department-wide rollout, the implementation team closely monitors the usage of the digital tool for rebar cutting optimization and evaluates its adoption rate. Each active and ongoing project is tracked to verify that the engineering teams are using the algorithm for rebar cutting plan and gathering any related information on issues which may arise. Measurable project performance indicators are monitored in this phase, such as the average rebar waste percentage per project, total material cost saved, and time spent in planning of rebar cutting versus benchmarks from before the tool's introduction. Management dashboards or periodic reports can be established in order to compare these metrics across projects by highlighting improvements and/or outliers. If any area of projects starts lagging in adoption, the implementation team should investigate and address barriers that have arisen. Additional training and/or adjustments in workflows might be provided to respond to such barriers. Throughout this phase, regular check-ins like weekly meetings can be held for users to share experiences, which not only helps identify common issues but also spreads useful tips among departments by further encouraging the use of the digital optimization tool (Jaaron et al., 2021). Moreover, the expert-users from each department have to be identified to foster interoperability, collaboration and communication within departments, which would further promote integrating the tool into routine operations.

Certainly, Company A's leadership should visibly support the deployment by communicating the importance of the new tool and recognize teams which effectively use the software to further reinforce a culture of acceptance (step 'Reinforcement'). As stated in Changwo (2022), non-financial rewards are as important as financial rewards, thus, could be effectively used in this step.

By the end of Phase 3, the rebar cutting optimization algorithm should be in active use company-wide for related projects, with the majority of engineers and project managers incorporating it into their standard workflow. The results in the forms of cumulative material

savings, cost reductions, and efficiency gains are expected for the algorithm to become evident at an organizational level, validating the benefits observed in the pilot on a larger scale.

Phase 4: Full-scale integration and continuous improvement

The aim of the Phase 4 is the transition of the organization from simply using the new digital tool to fully integrating it into Company A's standard business processes and culture. In this final phase, the algorithm for rebar cutting optimization is to be formally embedded into the company's Standard Operating Procedures (SOPs) for project planning and execution (Nakagawa, 2005). For instance, project management checklists and SOP documents should be updated to include a step for running the rebar cutting optimization for every project's reinforcement plan. Procurement procedures should be revised to account for optimized cutting plans by ensuring that rebar orders are placed in accordance with the outputs of the algorithm. These steps are necessary to make the digital tool to be a mandatory and routine part of the executions of projects, rather than an optional tool.

At this stage, long-term support and improvement mechanisms should also be established. Company A can set up a continuous improvement program for the usage of the tool in the form of quarterly or biannual reviews on the tool's performance across projects, and a mechanism for users to submit improvement ideas and/or report any new challenges (Kalman, 2024). The algorithm's development team remains involved to provide updates or new features as needed. To ensure sustainability of the change, performance metrics must continue to be tracked long-term and even suggested to be a part of Company A's operational KPIs (key performance indicators) reported to senior management. Given this, the digital tool's scope and implementation can further expand by supporting continuous improvement. The reduction in steel waste directly contributes to the company's sustainability goals (less material waste and lower carbon footprint for projects) and cost efficiency targets (avoiding over-purchase of rebar and reducing handling costs). Moreover, the use of a digital rebar cutting optimization tool also fits into Company A's broader digital transformation initiatives and demonstrates the efficiency of data-driven decision tools which can improve traditional construction processes. By the end of Phase 4, the rebar cutting optimization algorithm is not only to be fully deployed but also become the standard operational procedure for the organization. This full integration ensures that the financial, operational gains can be sustained over the long term, and that the organization maintains a mindset of continuous improvement.

5.2. Stakeholder roles and governance

For the implementation and integration of the digital tool into Company A’s operations, identifying stakeholder roles and management tactics should be specified.

5.2.1. Roles and responsibilities

The efficient deployment of the rebar cutting optimization tool is possible when the company stakeholders have a clear understanding of their roles and responsibilities, thus, the RACI matrix outlining the key stakeholders involved and their corresponding roles (responsible, accountable, consulted, informed) are assigned in the Table 5.1 below. The table was constructed based on the research of Lee et al. (2021); Mansour et al. (2024); Khan and Quraishi (2014). The following strategy reduces ambiguities and enhances efficiency during the implementation of the tool.

Table 5.1. RACI matrix of stakeholders

| Stakeholder | Responsible (R) | Accountable (A) | Consulted (C) | Informed (I) |
|---------------------------|----------------------------|----------------------------|--------------------------|-------------------------|
| Project manager | R | | | I |
| BIM manager | R | | C | |
| Procurement head | R | | C | |
| On-site engineer | R | | | I |
| IT support team | R | | | I |
| Quality assurance manager | | A | C | |
| Senior management | | A | | I |

| Stakeholder | Responsible (R) | Accountable (A) | Consulted (C) | Informed (I) |
|------------------------|----------------------------|----------------------------|--------------------------|-------------------------|
| Training coordinator | R | | | |
| Change management lead | R | | C | |

Note:

Responsible (R): Individuals who perform the work to achieve the task;

Accountable (A): Individuals who are accountable for the correct and thorough completion of the task;

Consulted (C): Individuals whose opinions are sought and needed;

Informed (I): Individuals kept up-to-date on implementation progress.

5.2.2. Stakeholder engagement strategy

Followed by assigning the roles and responsibilities, the effectiveness of the digital tool integration is enhanced by implementing the effective stakeholder engagement strategy. By utilizing the PMBOK stakeholder engagement model (Adhi & Muslim, 2023), the stakeholders have been identified and shown in Table 5.1 along with their assigned roles. However, following that, the engagement plan, execution and monitoring strategies must be thoroughly planned to ensure a smooth integration. The PMBOK model itself consists of five steps as follows:

1. Identification of all individuals involved, and groups affected by the digital tool, including all internal and external stakeholders;
2. Analysis of the stakeholders' interests, influence and their potential impact;
3. Engagement planning by developing effective engagement strategies, ensuring that needs and expectations are addressed;
4. Execution of the strategies by smooth and effective communication and collaboration;
5. Monitoring and controlling through regular reviews and making adjustments if necessary.

Based on this, the capstone project proposed can systematically foster a collaborative environment inside and outside of Company A for successful adoption of the tool. As evidenced by Yu and Leung (2018), structured modeling can raise stakeholders’ interests and engage in the decision-making process, also it is expected to achieve stakeholders’ satisfaction throughout the implementation process while using the model outlined above.

5.2.3. Value innovation using the ERRC Framework

As discussed in 5.2.2, it is crucial to engage stakeholders and raise their engagement through raising awareness and interest. One of the efficient ways is applying the Blue Ocean strategy using ERRC framework (Figure 5.2), which shows that the value proposition for stakeholders can be redefined in order to enhance the adoption and effectiveness of the tool.

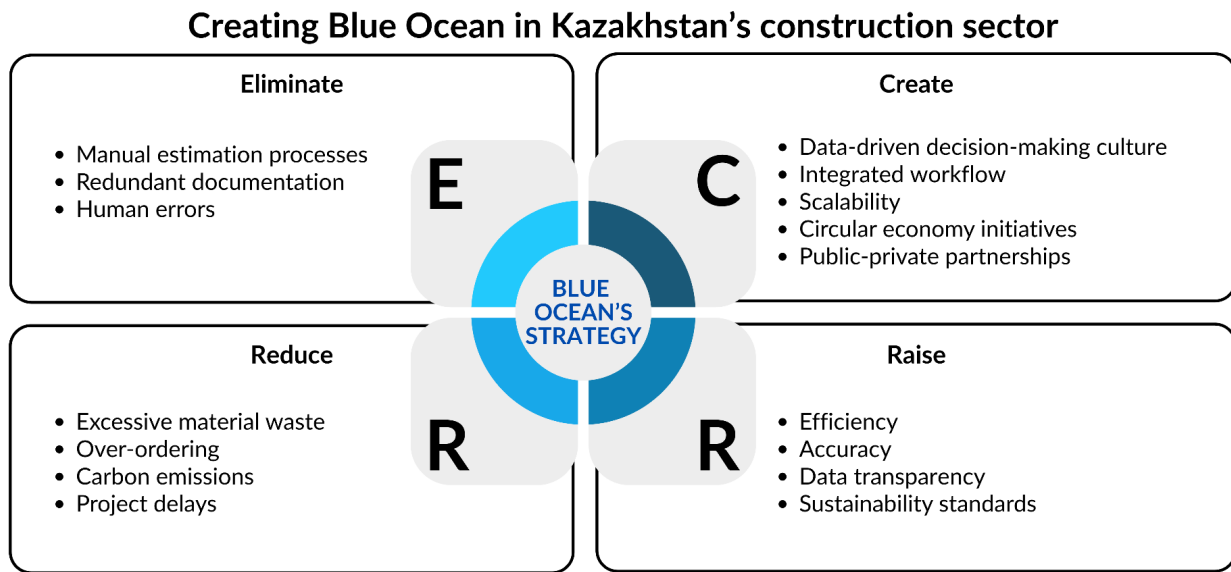


Figure 5.2. Application of the Four Actions framework to create a Blue Ocean in construction sector using the rebar cutting optimization tool

As evidenced, the rebar cutting digital optimization tool creates a blue ocean for Company A by addressing the inefficiencies in the construction sector. This tool could fundamentally transform the rebar use and ordering processes. It was identified that manual processes, human errors and redundant documentation are eliminated using the digitized form of calculations. Over-ordering which is in current practice for Company A, and total waste along with carbon emissions

can significantly be reduced by precise optimization strategy. This improves project timelines and reduces costs as well. The integration could also raise the efficiency of work, accuracy of cutting also supported by data transparency. Moreover, the digital tool creates a data-driven decision-making culture fostering integrated workflows across different departments of the Company A. Such innovation could not only enhance the operational performance of Company A, but also position the company as a leader in the construction industry in Kazakhstan exemplifying sustainable and data-driven, digitally transforming construction management. Finally, Company A could leverage the digital tool in order to foster circular economy initiatives of Kazakhstan as well as public-private partnerships to create new digital tools for further digitalization purposes of the construction industry.

5.3. KPIs and monitoring

5.3.1. Key performance indicators

There are several key performance indicators (KPIs) as identified in section 4, which could also be used to evaluate the performance and impact of the rebar cutting rebar optimization tool (Rahimi & Maghrebi, 2022). In order to ensure alignment with Lean Construction objectives, the following KPIs have been identified:

- *Rebar utilization rate*: measures the percentage of rebar used in comparison to the amount of ordered, the higher the rate, the higher the effectiveness of the material usage.
- *Procurement efficiency score*: assesses the timelines and accuracy of rebar orders, the higher the score, the better the supplier coordination.
- *Lead time*: duration between ordering the rebar till delivery, reduced lead time indicates improved the supply chain efficiency.
- *Total reusable waste*: measures the rebar waste that was left after the procurement step and not utilized during the project execution.
- *Total non-reusable waste*: measures the rebar waste that was left over after improper cutting and cannot be used further, the higher the waste, the lower the efficiency.

- *Efficiency*: measures the percentage of rebar used in comparison to the amount required for the project calculated by the digital tool, the higher the rate, the higher the effectiveness of the material usage.

5.3.2. Monitoring tools

Effectiveness of the adoption of the tool and its deployment can be monitored by the KPIs above as well as the facilitating regular reporting mechanisms as below:

- *BIM-integrated dashboards*: provide the real-time trackable visual representations of KPI metrics which also are linked to the BIM systems (Magill et al., 2020).
- *Monthly/quarterly reports*: offer detailed analyses of trends on digital tool’s performance and highlights areas for improvement (Jääskeläinen, 2023).
- *Stakeholder feedback surveys*: help to gather feedback/insights on the tool from on-site engineers, procurement teams, and management, ensuring that qualitative feedback complements quantitative data (Hammond et al., 2022).

Systematically tracking using these strategies can help to monitor deployment of the tool by Company A’s stakeholders and ensure the continuous improvement.

5.4. Risk management

Effective risk management is required for the successful implementation of the rebar cutting optimization tool, thus, Table 5.2 describes the potential risks which might occur during the implementation of the digital tool, as well as their corresponding mitigation strategies aligning with the Lean Construction principles.

Table 5.2. Risk matrix for implementation of the rebar cutting optimization tool

| Risk | | Probability | Impact | Risk level | Mitigation strategy |
|------|---------------------------------|-------------|--------|------------|---|
| R1 | Resistance to change from staff | H | H | H | Conduct comprehensive training sessions |

| Risk | | Probability | Impact | Risk level | Mitigation strategy |
|------|--|-------------|--------|------------|--|
| R2 | Inaccurate data input leading to errors | M | H | H | Implement data validation checks and provide user training |
| R3 | Delays in procurement due to system adoption | L | M | L | Coordinate with procurement teams to align processes and timelines |
| R4 | Over-reliance on the tool without oversight | L | H | M | Establish regular audits and maintain manual oversight where necessary |

Note, L, M, H stand for low, medium and high respectively.

The risk management has been developed in accordance with the results of subsections 4.4-4.7, and recommendations by Company A representative.

5.5. People and training

5.5.1. Training strategies

As proposed in section 5.1, training has to be implemented for staff to ensure effective adoption and foster a culture of continuous improvement. Thus, workshops - explanatory sessions for stakeholders, namely, site engineers, procurement teams and project managers; onboarding sessions - structured, comprehensive orientations for new users, including newly admitted staff have to be introduced to provide practical experience with the digital tool’s functionalities and benefits. Regular updates and handouts with examples of best practices can further foster continuous learning.

5.5.2. Support mechanisms

The ongoing learning for users and addressing questions of stakeholders can be handled using the mechanisms like helpdesk, user guides with FAQs, and feedback channels. Thus, Company A could deliver dedicated technical support by navigating through the use of comprehensive documentation and platforms for receiving feedback.

5.6. Alignment with national policies

5.6.1. Circular economy integration

As mentioned in the Literature Review section (section 2), currently Kazakhstan is actively promoting principles of circular economy (CE), even though it is in its early stages yet (Zhidebekkyzy et al., 2023). The digital tool, proposed in the scope of this capstone project, directly supports the objectives of the CE by providing means to reduce construction waste through precise and optimized rebar cutting. The reduction in excess rebar usage promotes efficient resource utilization, thus, aligns with national efforts to implement sustainable practices in the construction sector (Zhaksybayeva et al., 2024).

5.6.2. Vision 2050 alignment

The “Kazakhstan-2050” strategy, announced by the former President of Republic of Kazakhstan in December, 2012, is one of the development strategies aimed to create a welfare society (*Strategies and Programs — Official Website of the President of the Republic of Kazakhstan*, n.d.). The implementation and integration of the tool proposed in our capstone project also aligns with the long-term priorities of this strategic vision and helps to implement economic pragmatism as well as supports knowledge sharing and retraining the existing systems. Moreover, the “Taza Kazakhstan” concept proposed for 2024-2029 period, is also supported as the digital tool is also aimed at enhancing environmental awareness and decreasing waste disposed (Musrepov, 2024). As discussed in section 4.6, the environmental implications of the tool also align with the “2060 Carbon Neutrality Strategy” focused on reducing carbon emissions and advancing circular business models (Musrepov, 2024). Thus, by integrating and implementing the

proposed digital tool, Company A supports Kazakhstan's 2050 vision with emphasis on modernization and competitiveness in the global market.

5.6.3. Public-private partnerships

Kazakhstan's government encourages public-private partnerships in order to advance development of the infrastructure and promotion of technological innovation (Sadykova, 2020). The rebar cutting optimization tool deployment presents opportunities for such public-private collaborations as well as fosters cooperation between different construction firms, government agencies and innovators. These collaborations in combination accelerate the adoption of new, digital construction technologies and contribute to national strategies' realization. Thus, it is considered that the digital tool developed in the scope of this project is a small step to foster such collaborations which could further foster innovation in the construction sector of the country.

6. Conclusions, limitations and future directions

Within the scope of the capstone project, the rebar cutting optimization tool was researched, analyzed and developed. Utilizing complex mathematical modelling, embedding genetic algorithm and intuitive digital interface, the tool greatly minimized waste material, suggesting a simplified procurement process resulting in reduced overall construction costs. Testing and verification on real construction projects showed the effectiveness of the digital tool. For instance, 40.5% decrease became possible on total waste, implying the difference between ordered and required rebar materials. Moreover, efficiency, measured by the proportion between required and used rebar masses, substantially increased from 77.7% for manual calculations to 89.1% using the digital tool proposed, also implying significant monetary savings. These obtained results are in line with broader national objectives of sustainable economic development and environmental protection outlined in Kazakhstan's 2050 Strategy. The project has also developed a formal strategic integration framework of the tool into Company A's operations using the ADKAR model, stakeholder governance RACI matrix, suggesting KPI measurements, risk management plans, and training strategies to support ongoing, long-term operational success.

Even though the digital tool developed under the scope of this work is tested, validated and showed significant improvements, there are still several limitations. First, the algorithm developed is dependent on the input data, any misinformation inside the input file may result in incorrect deliverables of cutting patterns generated. Thus, second, manual oversight is still required to validate and approve the results of the software. Moreover, the tool does not yet fully integrate with the procurement process, thus, non-automation of this can also be a limitation until further updates are made. Lastly, there are still chances of integration constraints with existing systems in the forms of file formats and/or interoperability for real-world settings. In such cases, custom development could be required to solve challenges.

While major achievements are reached, there are further explorations possible to scale this digital tool's impact. Such directions include both internal improvements and broader industry recommendations. At a national level, regulatory frameworks can be strengthened to support sustainable construction practices. Introduction of targeted subsidies, tax incentives for companies enhancing sustainability strategies such as using recyclable materials and CO₂ reduction, and investment in waste management infrastructure to facilitate faster adoption of digital optimization

tools across the construction industry. Public campaigns would inform the public about benefits of circular economy methodologies for the greater cultural support of material reuse and recycling practices. Within the construction industry, similar innovations and initiatives should be fostered. To achieve that, Company A and other construction firms should collaborate to institute material exchange platforms and certification programs for recycled materials to make sustainable practices accessible and economically viable. As stated, public-private partnerships could be encouraged to digitalize and further digitally transform the construction industry of Kazakhstan.

The digital tool developed can further be expanded and integrated into BIM for increased usage. There are possibilities of enhancing the code by applying into objects requiring two or more variables instead of one (diameter of the rebar) in our case. The examples include applications to drywalls and pipes for initial steps. Moreover, the technical developments for the rebar cutting optimization tool may be based on introducing artificial intelligence for predictive analytics to provide real-time data from the construction site. Automatically adjusting cutting patterns as per the changes happening on the project is also a future direction which can be realized. Continuous user feedback and regular updates to the web application will ensure that the tool remains in sync with the emerging trends in construction and user requirements.

Overall, the project presents not only a working, tested solution for Company A but also offers a scalable model for advancing digitization towards digital transformation, applying lean practices, and sustainability in the construction sector of Kazakhstan.

References

- Abdullah, Z. T. (2024). A sustainable recycling approach for construction: A case of remanufacturing waste rebar into steel nails. *Results in Engineering*, 23, 102777. <https://doi.org/10.1016/j.rineng.2024.102777>
- Adams, K., Clift, M., Environment Agency, & Killeen, S. (2008). The economic and environmental benefits of resource efficiency in construction. In *Science Report* [Report]. *Environment Agency*. <https://assets.publishing.service.gov.uk/media/5a7b9c92ed915d4147621820/scho0308bnrx-e-e.pdf>
- Adhi, A. B., & Muslim, F. (2023). Development of stakeholder engagement strategies to improve sustainable construction implementation based on lean construction principles in Indonesia. *Sustainability*, 15(7), 6053. <https://doi.org/10.3390/su15076053>
- Alhawamdeh, M. (2020). *An interpretivist approach for the development of a behavioural framework to support the adoption of waste minimisation behaviour of contractors: The case study of Jordan*. University of Salford. <https://usir.salford.ac.uk/id/eprint/60985/>
- Balashbaneh, A. T., Sher, W., Li, J., & Ashour, A. (2024). Systematic Review of construction waste Management Scenarios: Informing Life Cycle Sustainability Analysis. *Circular Economy and Sustainability*. <https://doi.org/10.1007/s43615-024-00424-z>
- Buitrago, J. (Ed.). (2016). *EVM as a “Key metric” for the performances in the LPS management*. ELAGEC 2016. https://www.researchgate.net/publication/308725680_EVM_as_a_Key_metric_for_the_performances_in_the_LPS_management
- Caro, D., Lodato, C., Damgaard, A., Cristóbal, J., Foster, G., Flachenecker, F., & Tonini, D. (2023). Environmental and socio-economic effects of construction and demolition waste recycling in the European Union. *The Science of the Total Environment*, 908, 168295. <https://doi.org/10.1016/j.scitotenv.2023.168295>
- Changwo, R. J. (2022). *Effect of employee involvement in change management on project performance: a case of the road construction industry in Nairobi County*. <http://hdl.handle.net/11071/13081>

- Chen, X., Chang-Richards, A. Y., Pelosi, A., Jia, Y., Shen, X., Siddiqui, M. K., & Yang, N. (2021). Implementation of technologies in the construction industry: a systematic review. *Engineering Construction & Architectural Management*, 29(8), 3181–3209. <https://doi.org/10.1108/ecam-02-2021-0172>
- Christis, M., Athanassiadis, A., & Vercalsteren, A. (2019). Implementation at a city level of circular economy strategies and climate change mitigation – the case of Brussels. *Journal of Cleaner Production*, 218, 511–520. <https://doi.org/10.1016/j.jclepro.2019.01.180>
- Construction and demolition waste: From downcycling towards closed- and open-loop recycling*. Sortiersysteme für die Entsorgungsindustrie - STADLER Anlagenbau GmbH. (2022, May 12). <https://w-stadler.de/en/company/news/detail/construction-and-demolition-waste-from-downcycling-towards-closed-and-open-loop-recycling>
- Construction and demolition waste*. (n.d.). *Environment*. https://environment.ec.europa.eu/topics/waste-and-recycling/construction-and-demolition-waste_en
- Construction and demolition waste (CDW) » Collectors*. (2018, April 5). *Collectors*. <https://www.collectors2020.eu/the-project/scope/construction-demolition-waste-cdw/>
- Construction works in Kazakhstan grown by 10.3% in 11 months, reaching 6.9 trillion tenge - Official Information Source of the Prime minister of the Republic of Kazakhstan*. (2024). @Primeministerkz. <https://primeminister.kz/en/news/construction-works-in-kazakhstan-grown-by-103-in-11-months-reaching-69-trillion-tenge-29449>
- Creasey, T. (2022, August 10). ADKAR: Core to the people side of change. *Prosci*. <https://www.prosci.com/blog/adkar-core-to-the-people-side-of-change>
- Durdyev, S., & Hosseini, M. R. (2019). Causes of delays on construction projects: a comprehensive list. *International Journal of Managing Projects in Business*, 13(1), 20–46. <https://doi.org/10.1108/ijmpb-09-2018-0178>
- Digital, P. (2023, May 2). The Last Planner System (LPS) - Powergreen Digital - Getting construction Digital. *Powergreen Digital*. <https://powergreendigital.com/the-last-planner-system-lps/>
- Ferhat Karaca, & Aidana Tleuken. (2023). Reforming Construction Waste Management for Circular Economy in Kazakhstan: A Cost–Benefit Analysis of Upgrading Construction and

- Demolition Waste Recycling Centres. *Recycling*, 9(1), 2–2.
<https://doi.org/10.3390/recycling9010002>
- Ferronato, N., Sirpa, R. C. F., Lizarazu, E. G. G., Conti, F., & Torretta, V. (2022). Construction and demolition waste recycling in developing cities: management and cost analysis. *Environmental Science and Pollution Research*, 30(9), 24377–24397.
<https://doi.org/10.1007/s11356-022-23502-x>
- Garcia, C., Caro, D., Foster, G., Pristera, G., Gallo, F., & Tonini, D. (2024). Techno-economic and environmental assessment of construction and demolition waste management in the European Union, *Publications of the European Union, Luxembourg*,
<https://doi:10.2760/721895, JRC135470>
- Gerber, D. J., Becerik-Gerber, B., Gehry Technologies Inc., & Kunz, A. (2010). Building Information Modeling and Lean Construction: Technology, Methodology and Advances from Practice. *Proceedings IGLC-18, July 2010, Technion, Haifa, Israel*, 684–685.
<https://iglcstorage.blob.core.windows.net/papers/attachment-d3132ca9-78ac-4c74-bd6b-4a9e7924df96.pdf>
- Ghisellini, P., Ripa, M., & Ulgiati, S. (2017). Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. *Journal of Cleaner Production*, 178, 618–643.
<https://doi.org/10.1016/j.jclepro.2017.11.207>
- Gilmore, P. C., & Gomory, R. E. (1961). A linear programming approach to the Cutting-Stock problem. *Operations Research*, 9(6), 849–859. <https://doi.org/10.1287/opre.9.6.849>
- Ginga, C. P., Ongpeng, J. M. C., & Daly, M. K. M. (2020). Circular Economy on Construction and Demolition Waste: A Literature Review on Material Recovery and Production. *Materials (Basel, Switzerland)*, 13(13), 2970. <https://doi.org/10.3390/ma13132970>
- Glotzbach, R. (2024). Current and prevalent technologies in web curriculum. *Education and New Developments 2024 – Volume 1*. <https://doi.org/10.36315/2024v1end019>.
- Grinberg, M. (2018). *Flask web development: Developing web applications with python*. O'Reilly.
- Hammond, E. B., Coulon, F., Hallett, S. H., Thomas, R., Hardy, D., & Beriro, D. J. (2022). Digital tools for brownfield redevelopment: Stakeholder perspectives and opportunities.

- Journal of Environmental Management*, 325, 116393.
<https://doi.org/10.1016/j.jenvman.2022.116393>
- Heigermoser, D., De Soto, B. G., Abbott, E. L. S., & Chua, D. K. H. (2019). BIM-based Last Planner System tool for improving construction project management. *Automation in Construction*, 104, 246–254. <https://doi.org/10.1016/j.autcon.2019.03.019>
- Holland, J. H. (1975). *Adaptation in natural and artificial systems*.
<https://dl.acm.org/citation.cfm?id=129194>
- Jaaron, A. A., Hijazi, I. H., & Musleh, K. I. Y. (2021). A conceptual model for adoption of BIM in construction projects: ADKAR as an integrative model of change management. *Technology Analysis and Strategic Management*, 34(6), 655–667.
<https://doi.org/10.1080/09537325.2021.1915975>
- Jääskeläinen, P. (2023). *Performance reporting tools, integrability and information flow*. Theseus. <https://www.theseus.fi/handle/10024/798446>
- Jahanger, Q. K., Louis, J., & Trejo, D. (2022). Implementation framework to facilitate digitalization of construction-phase information management by project owners. *Journal of Information Technology in Construction*, 27, 529–547.
<https://doi.org/10.36680/j.itcon.2022.026>
- Jacob Ewing & Chrystal Denys (2024, April 4). *Kazakhstan Environmental Technology Waste Management Opportunities*. International Trade Administration | Trade.gov.
<https://www.trade.gov/market-intelligence/kazakhstan-environmental-technology-waste-management-opportunities>
- Jenewattananond, K. (2017, May 24). *Change management in Thai procurement organization: a case study in a Thai construction company*.
<https://archive.cm.mahidol.ac.th/handle/123456789/2076>
- Johnson, D. S. (1974). Fast algorithms for bin packing. *Journal of Computer and System Sciences*, 8(3), 272–314. [https://doi.org/10.1016/s0022-0000\(74\)80026-7](https://doi.org/10.1016/s0022-0000(74)80026-7)
- Kalman, F. (2024, October 17). *Need to implement construction tech? Use this process*. Built | the Bluebeam Blog. <https://blog.bluebeam.com/construction-technology-implementation-process/#:~:text=Now%20it%E2%80%99s%20time%20to%20put,scale%20rollout>
- Karaca, F., & Tleuken, A. (2023). Reforming Construction Waste Management for Circular Economy in Kazakhstan: A Cost–Benefit Analysis of Upgrading construction and

- Demolition waste Recycling Centres. *Recycling*, 9(1), 2.
<https://doi.org/10.3390/recycling9010002>
- Kazakhstan Construction Market Size, Trend Analysis by Sector, Competitive Landscape and Forecast to 2028 - H2 Update*. (2024, October 18). Market Research Reports & Consulting | GlobalData UK Ltd. <https://www.globaldata.com/store/report/kazakhstan-construction-market-analysis/>
- Khan, P., & Quraishi, K. A. (2014). Impact of RACI on Delivery and Outcome of Software Development Projects. *2014 Fourth International Conference on Advanced Computing & Communication Technologies*. <https://doi.org/10.1109/acct.2014.66>
- Kim, S., Hong, W., & Joo, J. (2004). Algorithms for reducing the waste rate of reinforcement bars. *Journal of Asian Architecture and Building Engineering*, 3(1), 17–23.
<https://doi.org/10.3130/jaabe.3.17>
- Korte, B., & Vygen, J. (2012). *Combinatorial Optimization: Theory and Algorithms*. <http://ci.nii.ac.jp/ncid/BB0476666X>
- Kwan, S. (2024, October 4). *Kazakhstan Recycles 24% of Waste It Produces - The Times Of Central Asia*. The Times of Central Asia. <https://timesca.com/kazakhstan-recycles-24-of-waste-it-produces/>
- Kwon, K., Kim, D., & Kim, S. (2021). Cutting Waste Minimization of REBAR for Sustainable Structural Work: A Systematic Literature review. *Sustainability*, 13(11), 5929.
<https://doi.org/10.3390/su13115929>
- Lee, W., Lee, S., Jin, C., & Hyun, C. (2021). Development of the RACI model for processes of the closure phase in construction programs. *Sustainability*, 13(4), 1806.
<https://doi.org/10.3390/su13041806>
- Legal Lens on Industrial Waste in Kazakhstan | Article | Chambers and Partners*. (2024). Chambers.com. <https://chambers.com/articles/legal-lens-on-industrial-waste-in-kazakhstan>
- Leppänen, J. (2024). *Change management in ERP system transition : a case study of procurement department at Meyer Turku Shipyard*. Theseus.
<https://www.theseus.fi/handle/10024/876256>
- Li, Y., & Solís, J. (2018). *A STRUCTURED LITERATURE REVIEW: VALUE STREAM MAPPING (VSM) IN CONSTRUCTION INDUSTRY* [Master's thesis, Texas A&M University, College Station]. <https://core.ac.uk/download/pdf/154406141.pdf>

- Li, C. Z., Zhao, Y., Xiao, B., Yu, B., Tam, V. W. Y., Chen, Z., & Ya, Y. (2020). Research trend of the application of information technologies in construction and demolition waste management. *Journal of Cleaner Production*, 263, 121458.
<https://doi.org/10.1016/j.jclepro.2020.121458>
- Liu, J., Yi, Y., & Wang, X. (2020). Exploring factors influencing construction waste reduction: A structural equation modeling approach. *Journal of Cleaner Production*, 276, 123185.
<https://doi.org/10.1016/j.jclepro.2020.123185>
- Lu, W., & Yuan, H. (2013). Investigating waste reduction potential in the upstream processes of offshore prefabrication construction. *Renewable and Sustainable Energy Reviews*, 28, 804–811. <https://doi.org/10.1016/j.rser.2013.08.048>
- Magill, L. J., Jafarifar, N., Watson, A., & Omotayo, T. (2020). 4D BIM integrated construction supply chain logistics to optimise on-site production. *International Journal of Construction Management*, 22(12), 2325–2334. <https://doi.org/10.1080/15623599.2020.1786623>
- Mansour, D., Elsayad, N., & Sheta, S. (2024). Strategies for Overcoming Challenges in Promoting a Socially-More Responsive Code of Building Information Modeling in Egypt. *International Society for the Study of Vernacular Settlements*, 11(2), 210–229.
<https://doi.org/10.61275/isvsej-2024-11-02-14>
- Mendigaliyev, K.Y. (2023). THE CURRENT STATE OF THE CONSTRUCTION INDUSTRY OF THE REPUBLIC OF KAZAKHSTAN: DESCRIPTIVE ANALYSIS. «Вестник НАН РК», 405(5), 484–494. <https://doi.org/10.32014/2023.2518-1467.604>
- Moreo, A., Romero, M., Castro, J., & Zurita, J. (2012). FAQtory: A framework to provide high-quality FAQ retrieval systems. *Expert Systems With Applications*, 39(14), 11525–11534.
<https://doi.org/10.1016/j.eswa.2012.02.130>
- Musrepov, G. (2024, November 13). Paving the way for a circular economy in the consumer goods and retail industry. *KPMG*. <https://kpmg.com/kz/en/home/insights/2024/11/paving-the-way-for-a-circular-economy.html>
- Nakagawa, Y. (2005). IMPORTANCE OF STANDARD OPERATING PROCEDURE DOCUMENTS AND VISUALIZATION TO IMPLEMENT LEAN CONSTRUCTION. In *Proceedings IGLC-13, July 2005, Sydney, Australia* (pp. 207–208).
<https://leanconstruction.org.uk/wp-content/uploads/2018/09/Nakagawa-2005-Importance-of-Standard-Operating-Procedure-Documents-and-Visualization.pdf>

- Nikakhtar, A., Hosseini, A. A., Wong, K. Y., & Zavichi, A. (2015). Application of lean construction principles to reduce construction process waste using computer simulation: a case study. *International Journal of Services and Operations Management*, 20(4), 461. <https://doi.org/10.1504/ij som.2015.068528>
- Nurly Zhol 2020-2025. (n.d.). Idfrk.kz. <https://idfrk.kz/en/products/state-programs/nurly-zhol-2020-2025/>
- Osmani, M. (2012). Construction waste minimization in the UK: current pressures for change and approaches. *Procedia-Social and behavioral sciences*, 40, 37-40.
- Papadaki, D., Nikolaou, D. A., & Assimakopoulos, M. N. (2022). Circular environmental impact of recycled building materials and residential renewable energy. *Sustainability*, 14(7), 4039. <https://doi.org/10.3390/su14074039>
- Past, V., Yaghmaeian, K., Naderi, M., & Naderi, N. (2023). Management of the construction and demolition waste (CDW) and determination of the best disposal alternative by FAHP (Fuzzy Analytic Hierarchy Process): A case study of Tehran, Iran. *Journal of the Air & Waste Management Association*, 73(4), 271–284. <https://doi.org/10.1080/10962247.2023.2178542>
- Rahimi, Z., & Maghrebi, M. (2022). Minimizing rebar cost using design and construction integration. *Automation in Construction*, 147, 104701. <https://doi.org/10.1016/j.autcon.2022.104701>
- Ray, S., Haque, M., Sakib, M. N., Mita, A. F., Rahman, M. M., & Tanmoy, B. B. (2021). Use of ceramic wastes as aggregates in concrete production: A review. *Journal of Building Engineering*, 43, 102567. <https://doi.org/10.1016/j.jobe.2021.102567>
- Rayhan, D. S. A., & Bhuiyan, I. U. (2023). Review of construction and demolition waste management tools and frameworks with the classification, causes, and impacts of the waste. *Waste Disposal & Sustainable Energy*. <https://doi.org/10.1007/s42768-023-00166-y>
- Samal, C. G., Biswal, D. R., Udgata, G., & Pradhan, S. K. (2025). Estimation, Classification, and Prediction of construction and demolition waste using Machine Learning for Sustainable Waste Management: A Critical review. *Construction Materials*, 5(1), 10. <https://doi.org/10.3390/constrmater5010010>
- Sadykova, Z. B. (2020). *Public-Private partnership in conditions of innovative development of Kazakhstan*. Questa Soft. <https://www.ceeol.com/search/article-detail?id=920968>

- Sbiti, M., Beddiar, K., Beladjine, D., Perrault, R., & Mazari, B. (2021). Toward BIM and LPS data Integration for Lean Site Project Management: A State-of-the-Art Review and Recommendations. *Buildings*, 11(5), 196. <https://doi.org/10.3390/buildings11050196>
- Schnell, P., Haag, P., & Jünger, H. C. (2022). Implementation of Digital Technologies in Construction Companies: Establishing a Holistic Process which Addresses Current Barriers. *Businesses*, 3(1), 1–18. <https://doi.org/10.3390/businesses3010001>
- Setiawan, N. I., Tumanggor, O. S. P., & Purba, H. H. (2021). Value Stream Mapping: Literature review and implications for service industry. *Jurnal Sistem Teknik Industri*, 23(2), 155–166. <https://doi.org/10.32734/jsti.v23i2.6038>
- Sherov, K., Serova, R., Yessirkepova, A., Mussayev, M., Zhanakov, K., Smailova, B., Turusbekova, A., & Mazhitova, L. (2021b). Enhancing the efficiency of rebar use in reinforced concrete products' manufacturing. *IOP Conference Series Materials Science and Engineering*, 1047(1), 012025. <https://doi.org/10.1088/1757-899x/1047/1/012025>
- Silva, R., De Brito, J., & Dhir, R. (2014). Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Construction and Building Materials*, 65, 201–217. <https://doi.org/10.1016/j.conbuildmat.2014.04.117>
- Simanjuntak, P. (2023). Digital technology usage influence on the effectiveness of the construction implementation team. *International Journal of Social Service and Research*, 3(2), 460–472. <https://doi.org/10.46799/ijssr.v3i2.267>
- Soto-Paz, J., Arroyo, O., Torres-Guevara, L., Parra-Orobio, B., & Casallas-Ojeda, M. (2023). The circular Economy in the construction and demolition Waste Management: A Comparative analysis in Emerging and Developed countries. *Journal of Building Engineering*, 78, <https://doi.org/10.1016/j.jobe.2023.107724>
- Strategies and programs — Official website of the President of the Republic of Kazakhstan.* (n.d.). Akorda.kz. https://www.akorda.kz/en/official_documents/strategies_and_programs
- Tam, V. W. (2008). Economic comparison of concrete recycling: A case study approach. *Resources, conservation and recycling*, 52(5), 821-828.
- Torgautov, B., Zhanabayev, A., Tleuken, A., Turkyilmaz, A., Mustafa, M., & Karaca, F. (2021). Circular Economy: Challenges and opportunities in the construction sector of Kazakhstan. *Buildings*, 11(11), 501. <https://doi.org/10.3390/buildings11110501>

- Tyagi, S. & C. a. & C. X. & Y. K. (2015). Value stream mapping to reduce the lead-time of a product development process. *ideas.repec.org*.
<https://ideas.repec.org/a/eee/proeco/v160y2015icp202-212.html>
- Uvarova, S. S., Orlov, A. K., & Kankhva, V. S. (2023). Ensuring efficient implementation of lean construction projects using building information modeling. *Buildings*, 13(3), 770.
<https://doi.org/10.3390/buildings13030770>
- U.S. Environmental Protection Agency | US EPA. (2025, February 12). US EPA.
<https://www.epa.gov/>
- Vilventhan, A., Ram, V., & Sugumaran, S. (2019). Value stream mapping for identification and assessment of material waste in construction: A case study. *Waste Management & Research the Journal for a Sustainable Circular Economy*, 37(8), 815–825.
<https://doi.org/10.1177/0734242x19855429>
- Wang, M., Wang, C. C., Sepasgozar, S., & Zlatanova, S. (2020). A Systematic Review of Digital Technology Adoption in Off-Site Construction: Current Status and Future Direction towards Industry 4.0. *Buildings*, 10(11), 204. <https://doi.org/10.3390/buildings10110204>
- Wang, Z., Jia, L., Lv, J., & Huang, J. (2024). Minimization of rebar cutting waste using BIM and cutting Pattern-Oriented multiobjective optimization. *Journal of Construction Engineering and Management*, 150(11). <https://doi.org/10.1061/jcemd4.coeng-15104>
- Wäscher, G., Haußner, H., & Schumann, H. (2006). An improved typology of cutting and packing problems. *European Journal of Operational Research*, 183(3), 1109–1130.
<https://doi.org/10.1016/j.ejor.2005.12.047>
- Widjaja, D. D., Rachmawati, T. S. N., Kim, S., & Lee, S. (2023). An algorithm to minimize Near-Zero Rebar-Cutting waste and rebar usage of columns. *Sustainability*, 16(1), 308.
<https://doi.org/10.3390/su16010308>
- Yu, A. T. W., Wong, I., Wu, Z., & Poon, C.-S. (2021). Strategies for Effective Waste Reduction and Management of Building Construction Projects in Highly Urbanized Cities—A Case Study of Hong Kong. *Buildings*, 11(5), 214. mdpi.
<https://doi.org/10.3390/buildings11050214>
- Yu, J., & Leung, M. (2018). Structural stakeholder model in public engagement for construction development projects. *Journal of Construction Engineering and Management*, 144(6).
[https://doi.org/10.1061/\(asce\)co.1943-7862.0001462](https://doi.org/10.1061/(asce)co.1943-7862.0001462)

- Zhaksybayeva, N., Serikkyzy, A., Baktymbet, A., & Yousafzai, S. (2024). Circular shifts: insights into kazakhstan's circular business ecosystem. *Cogent Business & Management*, *11*(1). <https://doi.org/10.1080/23311975.2024.2431652>
- Zheng, C., Yi, C., & Lu, M. (2019). Integrated optimization of rebar detailing design and installation planning for waste reduction and productivity improvement. *Automation in Construction*, *101*, 32–47. <https://doi.org/10.1016/j.autcon.2019.01.012>
- Zhidebekkyzy, A., Temerbulatova, Z., Amangeldiyeva, B. A., & Sakhariyeva, A. (2023). Towards a Circular Economy: an Analysis of Kazakhstani case. *Farabi Journal of Social Sciences*, *143*(1). <https://doi.org/10.26577/be.2023.v143.i1.02>

Appendices

Appendix A. Construction waste management survey

The purpose of the survey is to understand the challenges the company faces in managing waste and optimizing waste management processes. Your feedback will help us develop strategies and tools to improve material efficiency and reduce waste on construction sites.

Section 1: General Information

1. **Company Name:**
2. **Position of Respondent:** (e.g., Project Manager, Engineer, Site Supervisor)
3. **Email address:**
4. **Classification of organizations by size**
 - small
 - medium
 - large
5. **Type of organization at most 1 choice(s)**
 - A Agriculture, forestry and fishing
 - B Mining and quarrying
 - C Manufacturing
 - D Electricity, gas, steam, hot water and air conditioning supply 35
 - E Water supply; waste collection, treatment and disposal, pollution control activities
 - F Construction
 - G Wholesale and retail trade; repair of motor vehicles and motorcycles
 - H Transport and warehousing
 - I Accommodation and food services
 - J Information and communication
 - K Financial and insurance activities
 - L Real estate activities
 - M Professional, scientific and technical activities
 - N Administrative and support service activities
 - O Public administration and defence; compulsory social security
 - P Education
 - Q Health care and social work activities
 - R Arts, entertainment and recreation
 - S Other service activities
 - T Activities of households employing domestic servants; activities of households producing goods and services for own consumption

- U Activities of extraterritorial organisations and bodies
6. I consent that any responses and information provided in this questionnaire may be used for the development of the capstone project
 - Yes
 - No
 - Yes, but only on condition that any information provided is anonymised, and that the data provided cannot be associated or linked to my organization *
 7. I agree to be contacted to further expand on the answers provided, if necessary.
 - Yes
 - No

Section 2: Current problem

In this section we ask you to select the three main waste categories that are generated at your site. Please select the categories that make up the largest proportion of waste at your site.

1. What types of waste do you generate on site? (Select **3 options** that apply)
 - Concrete, bricks, tiles, cement, and ceramics.
 - Bituminous mixtures, coal tar, and tar.
 - Insulation and asbestos materials.
 - Metallic waste.
 - Wood, glass, and plastic
 - Soil, stones, and dredging.
 - Adhesives and sealants.
 - Paints and varnishes.

Section 3: Waste type #1

Complete the following questions for the first waste category selected only

1. Please provide an approximate waste percentage for the option selected
-
2. What are the main causes for the waste category with the highest percentage? (Select all that apply)
 - Calculation errors
 - Project changes
 - Poor planning
 - Delivery delays
 - Insufficient personnel skills
 - Materials do not meet project requirements
 - Limited access to necessary tools or equipment
 - Other...

3. How much waste is generated in tons and dollar/tenge value?

4. How does this waste affect the project budget and cost overruns? (Select all that apply)
 - Increased material purchase costs
 - Additional labor costs
 - Additional storage or disposal costs
 - Delays affecting labor scheduling
 - Other...
5. Have these wastes caused budget overruns in previous projects?
 - Yes, often
 - Sometimes
 - Rarely
 - Never
6. How do you currently manage this waste?
 - Recycle
 - Use for other projects
 - Dispose of as waste
 - Storage for possible future use
 - Other...

Section 4: Waste type #2

Complete the following questions for the second waste category selected only

1. Please provide an approximate waste percentage for the option selected

2. What are the main causes for the waste category with the highest percentage? (Select all that apply)
 - Calculation errors
 - Project changes
 - Poor planning
 - Delivery delays
 - Insufficient personnel skills
 - Materials do not meet project requirements
 - Limited access to necessary tools or equipment
 - Other...
3. How much waste is generated in tons and dollar/tenge value?

4. How does this waste affect the project budget and cost overruns? (Select all that apply)
 - Increased material purchase costs
 - Additional labor costs

- Additional storage or disposal costs
 - Delays affecting labor scheduling
 - Other...
5. Have these wastes caused budget overruns in previous projects?
 - Yes, often
 - Sometimes
 - Rarely
 - Never
 6. How do you currently manage this waste?
 - Recycle
 - Use for other projects
 - Dispose of as waste
 - Storage for possible future use
 - Other...

Section 5: Waste type #3

Complete the following questions for the third waste category selected only

1. Please provide an approximate waste percentage for the option selected

2. What are the main causes for the waste category with the highest percentage? (Select all that apply)
 - Calculation errors
 - Project changes
 - Poor planning
 - Delivery delays
 - Insufficient personnel skills
 - Materials do not meet project requirements
 - Limited access to necessary tools or equipment
 - Other...
3. How much waste is generated in tons and dollar/tenge value?

4. How does this waste affect the project budget and cost overruns? (Select all that apply)
 - Increased material purchase costs
 - Additional labor costs
 - Additional storage or disposal costs
 - Delays affecting labor scheduling
 - Other...
5. Have these wastes caused budget overruns in previous projects?
 - Yes, often

- Sometimes
 - Rarely
 - Never
6. How do you currently manage this waste?
- Recycle
 - Use for other projects
 - Dispose of as waste
 - Storage for possible future use
 - Other...

Section 6: Additional feedback

1. Please provide any additional comments or insights regarding financial impacts, time constraints, or optimization needs for rebar management in your company:

Appendix B. Post-implementation survey: rebar waste optimization

Section 1: General information

1. Your Name/Title: (Optional)
2. Project Name/Location: (Optional)
3. What length of time have you been using the program for?
 - Less than 1 month
 - 1 to 3 months
 - 3 to 6 months
 - More than 6 months
4. How many projects have you applied this tool in? _____

Section 2: Time savings

1. For every project, how much time did your staff previously spend developing rebar cutting plans?
 - Under eight hours
 - 8–16 hours
 - Between 17 and 24 hours
 - More than 24 hours
2. Currently, how much time do you spend using the program developing rebar cutting plans for every project? _____

Section 3: Financial savings

1. Has using the program resulted in any cost savings?
 - Yes
 - No
 - Not sure
2. If so, in which spheres were expenses cut? (Select all that apply)
 - Rebar purchasing
 - Labour hours
 - Organization and disposal of storage

- Project delays
 - Others: _____
3. Show by how much you cut expenses. _____

Section 4: Waste reduction

1. Indicate the reduction in rebar waste: _____
2. Was the software easy to use?
 - Very simple
 - Easy
 - Neutral
 - Difficult
 - Really challenging

Section 5: Features and suggestions

1. Would you recommend this software to other construction projects/companies?
 - Yes
 - No
 - Maybe
2. Please share any additional comments:

Appendix C. Flowchart illustrating the greedy algorithm

