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Analysis of Egyptian Ministry of Defense E-Waste Processes and Management

June 2025

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ABSTRACT

This thesis presents an in-depth analysis of the E-waste management process used by the Egyptian Ministry of Defense (MOD), highlighting opportunities to improve efficiency and economic outcomes. Currently, E-waste is stored in centralized warehouses and sold every three months to private-sector buyers, a process that neglects the substantial potential value within discarded electronics. By adopting urban mining—extracting valuable metals such as gold, silver, copper, and palladium from electronic waste—MOD could recover resources internally and enhance sustainability. Many private-sector buyers lack a proper recycling infrastructure, often leading to environmentally harmful disposal practices and the loss of critical materials. Establishing internal recycling facilities would allow MOD to control the full process, increase revenue, and minimize environmental risks associated with improper E-waste handling. Recovered materials could directly support Egypt's defense industrial base, reducing reliance on imported resources and strengthening national supply chain resilience. This study includes a comparative cost-effectiveness analysis as well as detailed process mapping of both the current and proposed E-waste management systems. The findings show that, although internal recycling requires a higher initial investment, it ultimately delivers greater financial returns, stronger regulatory compliance, improved material flow, and better alignment with national sustainability.

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Col Omar Ahmed is an officer in the Egyptian Army**.** He is currently serving at the Egyptian Ministry of Defense and holds the rank of Colonel. COL Ahmed earned a Bachelor of Electrical Engineering from the Military Technical College in Cairo in 2003. He later earned a Master of Science in Electronic Engineering from the same college in 2020. He is now completing a master's degree in financial management at the Naval Postgraduate School, with an expected graduation date of June 2025. COL Ahmed's military assignments have included serving as the Maintenance Officer for the MILES Training System (Depot Workshop) for eight years. He also spent two years as a full-time master's student in Electronic Engineering. Following this, he served as a Custom Clearance Officer in the Export/Import Freights section of the A&A Department of the Egyptian Army. He continued in that department as a Procurement Officer for two years before being promoted to Chief of the Procurement Branch, where his responsibilities included overseeing procurement operations and contributing to financial reporting and fiscal budget execution. He is married and has three children—two boys and one girl. In his free time, COL Ahmed enjoys cycling, jogging, and exercising.

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LIST OF ACRONYMS AND ABBREVIATIONS

CBA	Cost–Benefit Analysis
CEA	Cost-Effectiveness Analysis
CPU	Control Processing Units
DIB	Defense Industrial Base
EEE	Electronic and Electrical Equipment
EoL	End-of-Life
E-waste	Electronic Waste
FOB	Free on Board
MOD	Ministry of Defense
MOE	Measurement of Effectiveness
PCB	Printed Circuit Board
RAM	Random Access Memory
StEP	Solve the E-waste Problem
TPS	Toyota Production System
UNU	United Nations University
WEEE	Waste of Electrical and Electronic Equipment
WPCB	Waste of Printed Circuit Board

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I. INTRODUCTION

The electronics sector is one of the world's most influential industries and has consistently expanded over recent decades (Atradius, 2024). Not only does it support substantial employment and foster technological innovation, it also drives a significant demand for raw materials, including precious metals and rare earth elements, which are limited in supply (Veit & Bernardes, 2015). As electronic and electrical device production continues to expand globally, the volume of outdated devices, which this thesis refers to as *electronic waste* (E-waste), increases significantly. This rise in E-waste is driven by rapid technological advancements that encourage consumers to frequently update their devices to keep pace with the latest features and performance enhancements.

"A mixture of metals can be found in waste of electrical and electronic equipment (WEEE), such as copper, iron, aluminum, brass and even precious metals, such as gold, silver and palladium" (Veit & Bernardes, 2015, p. 5). Extracting these elements from the WEEE by implementing the appropriate recycling system has both economic and environmental benefits. "E-waste is a new category of waste in all countries, and Egypt is not an exclusion. Egypt is among the top three countries in Africa with the highest E-waste generation in absolute quantities, amounting 0.37 million tons in 2016, with no proper management" (Abdelbasir et al., 2018, p. 16541). These amounts of E-waste not only have a negative environmental and health impact if they are not recycled properly but also represent untapped financial potential, a source of revenue that could be better accessed through recycling.

In the Egyptian Ministry of Defense (MOD), the maintenance of electronic and electrical equipment (EEE) and the pursuit of advancements in military weapon systems have led to the accumulation of hundreds of tons of E-waste over the past decade. However, the current disposal process for E-waste within the MOD lacks proper recycling systems to efficiently extract metals and valuable materials found in WEEE. Consequently, the Egyptian MOD may be missing a significant opportunity to invest in a recycling system beneficial to the MOD.

A. PROBLEM STATEMENT

The current MOD process for disposing of retired equipment and salvage spare parts is to sell this salvage E-waste to buyers (companies) in the private sector. Alternatively, this kind of E-waste can be processed through recycling plants to efficiently extract specific valuable minerals at the outcome of this process. These extracted minerals could be either used toward the raw materials needs of the MOD defense industrial base or sold to private-sector companies. Alternative MOD processes for E-waste may have economic and environmental benefits for the inventory management process in the MOD.

B. RESEARCH QUESTIONS

(1) Primary Research Question

The primary question is as follows: What are the potential benefits of implementing an internal E-waste recycling system in the MOD inventory management process, considering current market needs for raw materials and trends for E-waste resale?

(2) Secondary Research Question

The secondary question is as follows: What are the implications of the E-waste recycling system on the cost efficiency of the inventory management process in the MOD compared to the current outsourcing of E-waste disposal to private entities?

C. RESEARCH METHODOLOGY

This thesis starts with a background section (Chapter II) and literature review (Chapter III) focused on the current E-waste processes used across the world and analyzes the global trends in this field. Chapter IV presents a systematic analysis of the current E-waste management process within the Egyptian MOD. Initially, the existing procedures are mapped using the principles of process mapping and lean thinking to identify operational strengths and weaknesses. Following this analysis, a recycling system that has been successfully implemented in China is introduced as a potential model for adoption. This model is evaluated through a cost-effectiveness analysis (CEA), comparing the current practice of selling E-waste to private parties with the proposed recycling system. The goal of this methodology is to determine which approach is more beneficial for the Egyptian MOD, ultimately providing evidence-based recommendations for enhancing E-waste management practices, which are introduced in Chapter V.

D. SCOPE

This research focuses on comparing two distinct approaches to managing E-waste within the Egyptian MOD. The first approach involves the current practice of selling E-waste to private entities, while the second option explores the feasibility and advantages of implementing a recycling system internally. By evaluating these methods, the study aims to provide a comprehensive understanding of how each approach addresses the growing challenge of E-waste management in a cost-effective manner.

A significant emphasis of this research is on conducting a detailed CEA, which helps to assess the economic implications associated with each method. This analysis delves into the potential financial benefits and drawbacks of adopting a recycling process for E-waste in the MOD. By highlighting these economic factors, the study intends to inform decision-makers about the viability of transitioning to a more sustainable E-waste management practice, ultimately contributing to more informed resource allocation and strategic planning within the ministry.

To conclude, this chapter emphasized the critical importance of addressing the growing challenge of E-waste management, particularly within the MOD, as well as its broader environmental and economic implications. The next chapter provides a detailed exploration of the E-waste issue, discussing the classification of E-waste, its environmental and economic impacts, and the current trends in E-waste generation. Additionally, it presents projections for the quantities expected to be generated both globally and specifically within Egypt in the near future.

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II. BACKGROUND

The disposal of electronic and electrical equipment (EEE), commonly known as E-waste, is now one of the fastest-growing waste streams globally (Cayumil Montecino, 2016). E-waste encompasses a vast array of household and personal appliances routinely used in urban areas, including cell phones, computers, DVDs, scanners, fax machines, printers, tablets, microwaves, X-ray machines, and various scientific equipment (Afroz et al., 2013; Tuncuk et al., 2012).

The rapid pace of technological innovation has led to unprecedented consumption of EEE, resulting in substantial amounts of E-waste. If not managed properly, this E-waste poses serious threats to the economy, environment, and public health. However, when E-waste is recycled correctly, it can significantly reduce these harmful effects while conserving natural resources by recovering valuable materials and rare minerals during the recycling process (Cayumil Montecino, 2016). It is imperative to prioritize effective E-waste management to safeguard the environment and public health.

Recent research over the past decade has underscored the urgent global crisis posed by E-waste. In 2022, a staggering 62 million metric tons of electronic waste were generated worldwide, nearly doubling the amount produced since 2010 (Alves, 2024). Alarmingly, more than 75% of this E-waste remains unaccounted for due to insufficient waste management strategies (Alves, 2024). Projections indicate that by 2030, the amount of E-waste could soar past 80 million metric tons, bringing about dire consequences for the environment and public health 6/11/2025 3:09:00 PM. This critical scenario is prompting decision-makers around the globe to recognize the necessity for effective E-waste management solutions. Urgent action is needed to implement robust recycling processes and recovery systems. While challenges abound, now is the time to act to safeguard our planet for future generations (Alves, 2024).

A. E-WASTE CLASSIFICATIONS

The EEE disposal process that generates E-waste encompasses a variety of equipment and devices. For properly establishing the recycling option and efficiently identifying the recycling potential for E-waste, it is essential to characterize EEE products thoroughly by determining the physical and chemical properties of their component materials and assess their hazardousness (Veit & Bernardes, 2015).

According to the United Nations University (UNU), an effective classification system for E-waste statistics should group products based on similar functionalities, material compositions regarding hazardous and valuable contents, and comparable end-of-life characteristics (International Telecommunication Union [ITU], 2018). Moreover, items within each category should share a consistent average weight and lifespan distribution to streamline the quantitative evaluation of like products (Forti et al., 2018). Table 1 shows the main groups of the UNU classifications for E-waste.

Table 1. Main Groups of UNU Classifications of E-Waste. Adapted from Forti et al. (2018).

Primary Category	**Description**
Large Equipment	Bulky items such as household appliances like washing machines, dryers, photovoltaic panels, heating systems
Small Equipment	Smaller household appliances like toasters, kitchen equipment, kettles, and hair dryers
Temperature Exchange Equipment	Fridges, freezers, air conditioners, and different types of cooling systems
IT and Telecom Equipment	Desktop PCs (excl. monitors, accessories) professional small IT equipment (e.g., routers, mice, keyboards, external drives, and accessories)
Consumer Electronics	Portable audio and video devices (e.g., headphones, portable controls, MP3, e-readers, and GPS trackers)
Lighting Equipment	Lighting equipment (excl. LED and incandescent), compact fluorescent lamps (incl. retrofit and non-retrofit), and professional luminaires (offices, public-space, industry)
Screens and Displays	Flat display panel TVs (LCD, LED, plasma), cathode ray tube TVs

Proper disposal and recycling of E-waste are crucial to prevent environmental damage and recover valuable materials. The various categories of E-waste mentioned in Table 1 are considered a "recycling potential," which is a recent economic expression (Kanwal et al., 2023) used to indicate that the potential revenues from electronics recycling exceed the costs of collection, transport, and processing. Figure 1 shows the worldwide E-waste generated quantities per each category in 2022.

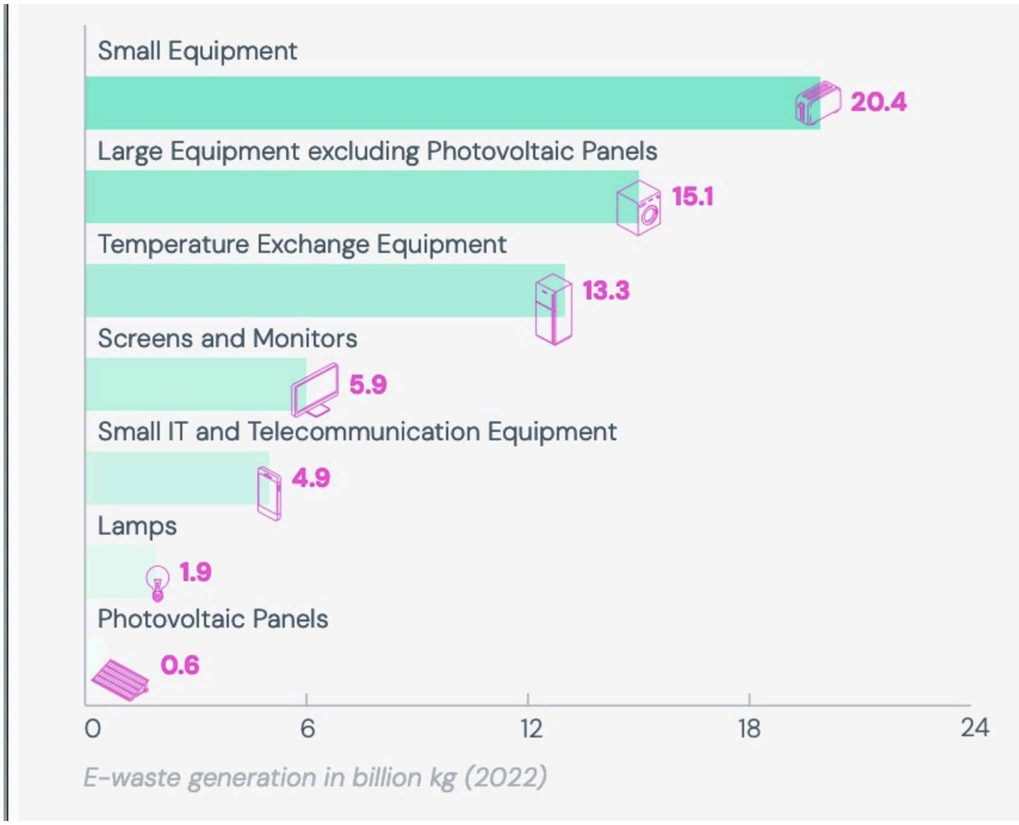

Figure 1. Worldwide E-Waste Generated in 2022 (by Category). Source: Baldé et al. (2024)

Increasing recycling rates is a key strategy for addressing the E-waste problem. Implementing effective processes to enhance the efficiency of recycling aims to maximize the benefits derived from recycling E-waste. This approach not only helps to close the loop on resource depletion but also minimizes the risks and negative impacts on both the environment and public health.

B. IMPLICATIONS OF IMPROPER MANAGEMENT OF E-WASTE

While E-waste is regarded as a significant secondary source of metallic raw materials, it also contains numerous hazardous substances that can adversely affect human health and the environment. These hazardous materials require specialized treatment and handling for proper disposal to mitigate their harmful impacts on both human health and the environment.

1. Environmental Impacts

According to data from the Global E-Waste Monitor, 73% of temperature exchange equipment worldwide is managed in an environmentally harmful manner (Baldé et al., 2024). Refrigerants are often released directly into the atmosphere. Additionally, even countries that offer safe degassing of refrigerants fail to effectively collect and manage all temperature exchange equipment.

According to Ohajinwa et al. (2018), the actions of informal recyclers in the E-waste dismantling process are severely damaging soil and land. These researchers explain that informal recyclers extract valuable metals from EEE while discarding the remaining parts, which contaminates the soil with hazardous and toxic materials. Furthermore, these recyclers often use methods that pollute the air, such as burning electrical cables to remove the insulation and collect the copper or aluminum inside (Ohajinwa et al., 2018).

As revealed in a 2024 Global E-Waste Monitor report by Baldé et al. (2024), E-waste is a significant environmental threat, as it contains dangerous substances like mercury and flame retardants, which are commonly found in electronic appliances and plastic materials. Furthermore, they add that every year around 58,000 kg of mercury and 45 million kg of plastics with toxic brominated flame retardants enter our environment due to inadequate E-waste management. It is crucial to take action to address this issue and ensure safe disposal practices to protect our planet and our health. Currently there are 17 billion kg of E-waste plastics in existence that urgently need to be recycled and treated using environmentally sound methods (Baldé et al., 2024).

Recycling E-waste by scavenging raw materials slows the rapid depletion of natural ores of raw materials extracted from E-waste recycling (Baldé et al., 2024). Globally, the recycling of E-waste as secondary raw material prevented the excavation of 900 billion kg of raw materials from natural resources and avoided 52 billion kg of CO_2-equivalent emissions in the environment (Baldé et al., 2024).

2. Economic Impacts

The economic implications of improper E-waste management are far-reaching and include costs related to resource management and recovery, public health, and environmental externalities from unmanaged hazardous substances and emissions.

Additionally, this waste fails to take advantage of opportunities to extract valuable resources from materials. The global economy suffers an estimated loss of at least $57 billion every year due to the disposal of valuable raw materials like iron, copper, and gold that could otherwise be recovered through proper recycling (Maes & Preston-Whyte, 2022).

C. E-WASTE QUANTITIES

This section focuses on recent E-waste quantities globally and in Egypt. In 2016, approximately 44.7 million tons of E-waste were generated globally, and this figure was expected to rise to 52.2 million tons by 2021, increasing at an annual rate of 3–4% (Baldé et al., 2017). But in 2022, 62 million tons of E-waste were generated globally, almost doubling the amount since 2010, and this amount is projected to increase to 82 million tons by 2030, as shown in Figure 2 (Baldé et al., 2024). Despite this surge, waste management efforts are still lacking, with more than 75% of E-waste unaccounted for (Alves, 2024). As projections estimate that E-waste will exceed 80 million metric tons by 2030, enhanced recycling and recovery systems will be essential, though significant challenges persist (Alves, 2024) . The annual rate of E-waste recycling from 2016 to 2022 was almost 6.75%, and the estimated rate was 3% to 4%; this reflects how the amount of E-waste is increasing more than the expected rates, which may cause an environmental crisis if E-waste is not recycled and managed properly to reduce its impact on human life and to benefit from the valuable and rare minerals included in E-waste. In Egypt, estimates were made for end-of-life (EoL) mobile phones, referring to devices that are no longer functional. Mobile phones, especially in developing countries, are one of the fastest-growing categories of electronic items reaching their end of use. Research has projected that by 2025, EoL mobile phones could reach 130 million units (Moossa et al., 2022). Furthermore, it was estimated that about 3 tons of gold and 31 tons of silver could potentially be recovered from these devices by 2025 (Moossa et al., 2022). This projection relied on the number of registered SIM cards in Egypt as an estimate for mobile phone use, adjusting for a 10% reduction to account for SIMs used only for data, dual SIM devices, inactive cards, and short-term usage by travelers (Shakra & Awny, 2017).

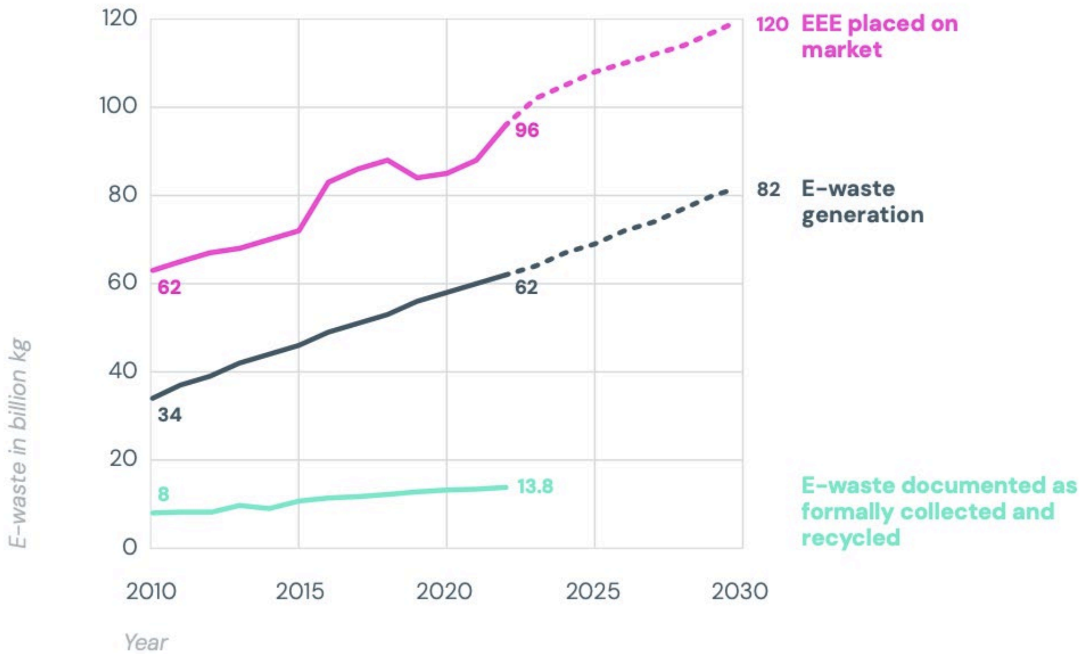

Figure 2. E-Waste Generated Globally (2010–2022). Source: Baldé et al., (2024).

To address the growing challenge of E-waste management, this chapter highlighted the environmental and economic implications of improper disposal and the opportunities presented by efficient recycling systems. The MOD faces significant gaps in its current practices, missing out on both financial gains and resource recovery potential. These insights establish the importance of adopting innovative approaches to optimize E-waste processes, particularly through internal recycling systems. The next chapter builds on this analysis by exploring CEA, process mapping, lean thinking, and successful E-waste recycling practices globally.

III. LITERATURE REVIEW

The objective of this literature review is to explore the practical frameworks that are essential for evaluating E-waste management strategies. It begins with a detailed review of cost-effectiveness analysis, a key methodology used to assess the financial and operational efficiency of alternative approaches. This is followed by an examination of process mapping and lean thinking principles, which are essential tools for identifying inefficiencies and streamlining operations. Also, this chapter explores global best practices in E-waste recycling, offering insights into how other nations have successfully addressed similar challenges. These elements provide the foundation for analyzing and comparing the Egyptian MOD's current E-waste management process with potential alternatives.

A. COST-EFFECTIVENESS ANALYSIS

Cost-effectiveness analysis (CEA) is a systematic approach used to evaluate the relative costs and outcomes of different programs. One of the earliest papers to discuss CEA states that "the practice of cost-effectiveness started when man first realized his resources were limited" (Quade, 1971, p. 1). CEA is particularly valuable in a resource-constrained environment helping decision-makers optimize resources per unit of effectiveness. Everyone engages in cost-effectiveness decisions, from a housewife managing household expenses within a set budget to a public utility deciding between nuclear and fossil fuel energy sources (Quade, 1971). CEA aims to determine and quantify the expenses associated with a program, linking these costs to specific indicators of the program's success (Cellini & Kee, 2015).

CEA shares similarities with the well-known cost–benefit analysis (CBA). Both methods assess the costs and benefits of different options, aiming to identify the alternative that delivers the most value to the desired outcome (Vacchio, 2024). CBA is a structured approach for assessing the direct and indirect costs and benefits, both private and social, linked to a policy decision (Coppola et al., 2022). "This method involves the extraction from the set of predicted impacts those for which monetary values can be obtained or estimated" (Coppola et al., 2022, p. 3). The difficulty in CBA lies in assigning monetary values, as many impacts cannot be directly measured using market prices and must instead be estimated by the analyst (Coppola et al., 2022). Evaluating the adoption of an E-waste recycling system within the Egyptian MOD presents significant challenges in monetizing intangible benefits. These benefits, such as environmental preservation and enhancement of inventory management, cannot be measured in monetary terms. As a result, traditional CBA, which relies heavily on assigning monetary values to both costs and benefits, may not be the most suitable method for this assessment.

"On the other hand, CEA is an economic evaluation technique that compares the relative costs and outcomes of different course of actions in order to assure the efficient use of investment resources" (Coppola et al., 2022, p. 3). The authors explain that the effectiveness of a measure is determined by how well it meets the anticipated objectives. Furthermore, they highlight that the primary benefit of using CEA over CBA is that CEA allows decision-makers to evaluate alternatives based on measurable outcomes rather than assigning monetary values to those outcomes. However, the main limitation of using CEA is that while it identifies the most economical method to reach a specific goal, it does not assess whether achieving that goal is truly worth the associated expenses (Coppola et al., 2022). The analysis in this research assesses the cost for the MOD to implement an E-waste recycling system and evaluates how effectively the system can achieve the organization objectives compared to its current E-waste management practices. However, determining whether the cost of E-waste recycling is justified by its impact on the desired outcome is a subjective decision, ultimately made by Army leaders.

B. THE CONCEPT OF LEAN THINKING

The Japanese automaker Toyota was the first to introduce and adopt this successful manufacturing process management concept in the early 20th century (Toyota Motor Company, 1973). They based the Toyota production system (TPS) on the lean thinking philosophy to increase manufacturing process efficiency, decrease production lines' resource waste, and decrease the incidence of defective products.

As a result of the company's impressive improvement (Rüttimann & Stöckli, 2016), the lean thinking concept spread to other large companies and enterprises such as

Intel and GM (Lombardi, 2018) that were looking to improve processes and manage resources efficiently in order to maximize the added value from resource consumption and remove waste from the process stream.

Not only were big businesses and corporations inspired by the lean methodology, but experts and researchers from around the globe were also motivated to fully understand the lean philosophy and best practices to efficiently implement this concept in real-world applications.

According to the TPS Basic handbook, the main pillars of the system are the concepts Just in Time and Jidoka (Figure 3). These basic concepts were the drivers of building quality in the production processes and separating automated processes from man-controlled processes (Toyota Motor Company, 1973).

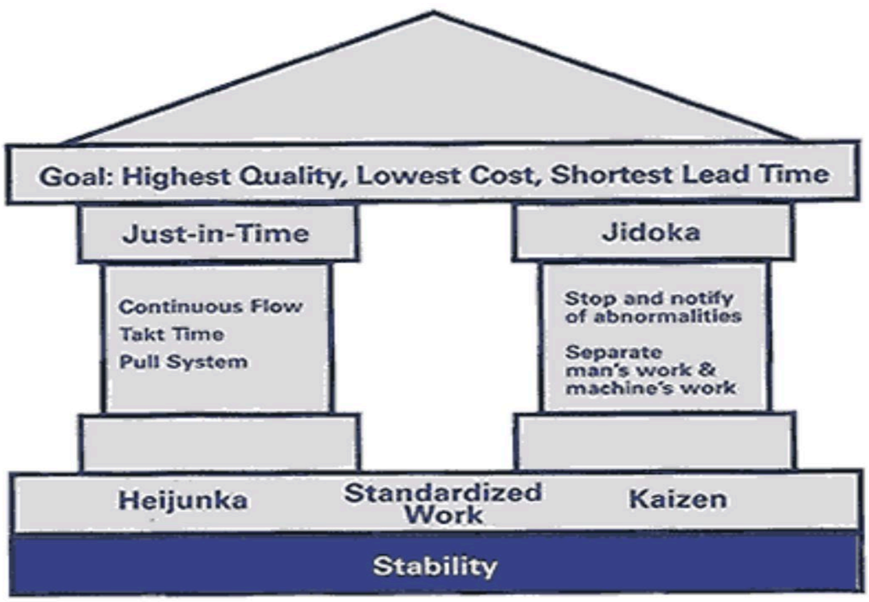

Figure 3. Toyota Production System (TPS) House. Source: Toyota Motor Company (1973).

Moreover, Toyota implemented multiple organizational principles to address the concepts known as the 7 Wastes (Figure 4), which significantly reduced costs and the effort to maximize efficient use of resources as well as minimizing or eliminating activities that had no added value to either the product or the services (Sutherland & Bennett, 2007). The addressed sources of the 7 Wastes are as follows:

1. **Transportation:** Unnecessary movement of products or materials.
2. **Inventory:** Excess products or materials not being processed.
3. **Motion:** Unnecessary movements by people (e.g., walking, reaching).
4. **Waiting:** Idle time when resources are not being used.
5. **Overproduction:** Producing more than what is needed or before it is needed.
6. **Overprocessing:** Performing more work or using more resources than necessary.
7. **Defects:** Products or services that do not meet quality standards and require rework or scrapping (Sutherland & Bennett, 2007).

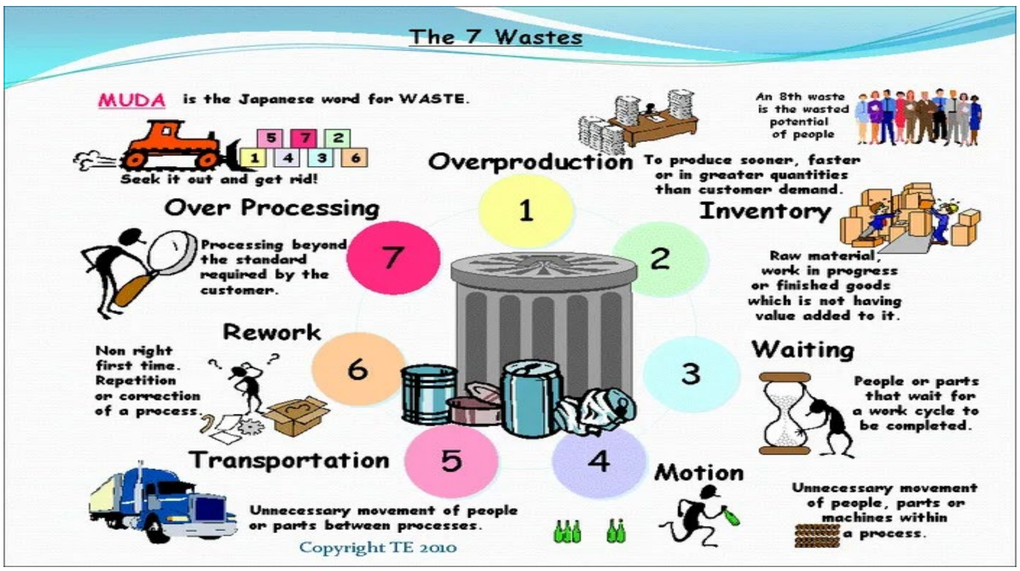

Figure 4. The 7 Wastes. Source: Lean Manufacturing Tools (2011)

The integration of the factors mentioned earlier, in line with the lean philosophy, helps create a framework for managing operations within an organization. This approach, combined with a focus on continuous improvement, enhances the capacity of systems that embrace this concept to achieve significant gains in both efficiency and effectiveness.

C. APPLYING THE LEAN THINKING CONCEPT FOR FORMULATING THE E-WASTE PROCESS MAPPING

Applying lean thinking to the E-waste recycling process can significantly enhance efficiency and reduce process waste. Some of the steps to be considered for creating a proper process mapping using lean principles are as follows (Chandra, 2019) :

1. **Define Value:** Address what value means in the context of E-waste recycling. This involves maximizing the recovery and extraction of valuable materials, minimizing the environmental impact, and ensuring compliance with regulations.
2. **Map the Value Stream:** Create a detailed map of the entire E-waste recycling process, from collection to final disposal. This includes identifying all steps involved, such as sorting, dismantling, shredding, and minerals recovery. Highlight both value-adding and non-value-adding (waste) activities.
3. **Create Flow:** Ensure that the process flows smoothly without interruptions. This might involve reorganizing the layout of the recycling facility to minimize transportation time and handling or implementing standard procedures to reduce variability.
4. **Establish Pull**: Implement a pull system where recycling activities are driven by demand rather than pushing materials through the process. This can help in managing inventory levels and reducing overproduction.
5. **Continuous Improvement:** Seek perfection of the process. This could involve regular Kaizen events to identify and eliminate waste, adopting new technologies for more efficient recycling, or training employees on lean principles.

By following these steps, E-waste recycling processes will be more efficient, sustainable, and compliant with regulations.

D. RECYCLING PROCESSES

This section discusses recycling processes for the waste of printed circuit boards (WPCBs). Printed circuit boards (PCBs), found in all types of electronic devices, are particularly valuable due to their composition, which includes copper and precious metals such as gold, silver, and palladium, making them an important source of secondary raw materials (Veit & Bernardes, 2015). The recycling of WPCBs generally begins with mechanical processing; typically this process starts with separating non-essential components, then cutting the board into smaller pieces, and finally milling them into fine particles for further use (Das et al., 2009). Mechanical processing is typically viewed as a preliminary treatment for material separation and involves various stages to segregate the components of WEEE (Hayes, 1993). Dismantling is a crucial and essential step in managing all types of E-waste by enabling the separation of specific components, particularly those that are either hazardous or contain valuable materials for further treatment (Abdelbasir et al., 2018). "Most of the recycle plants utilize manual dismantling. … A variety of tools is involved in the dismantling process for removing hazardous components and recovery of reusable or valuable components and materials" (Cui & Forssberg, 2003, p. 8). "After the dismantling process, WPCBs are subjected to some physical process which involves shredding to small pieces, using crusher and grinders followed by magnetic, eddy current and density separation techniques to separate metallic and non-metallic fractions" (Abdelbasir et al., 2018, p. 16536). Then the produced metal fractions undergo hydrometallurgical, pyrometallurgical, and electrometallurgical processes for more refining (Veit & Bernardes, 2015). The E-waste treatment process is shown in Figure 5 (Chancerel et al., 2009).

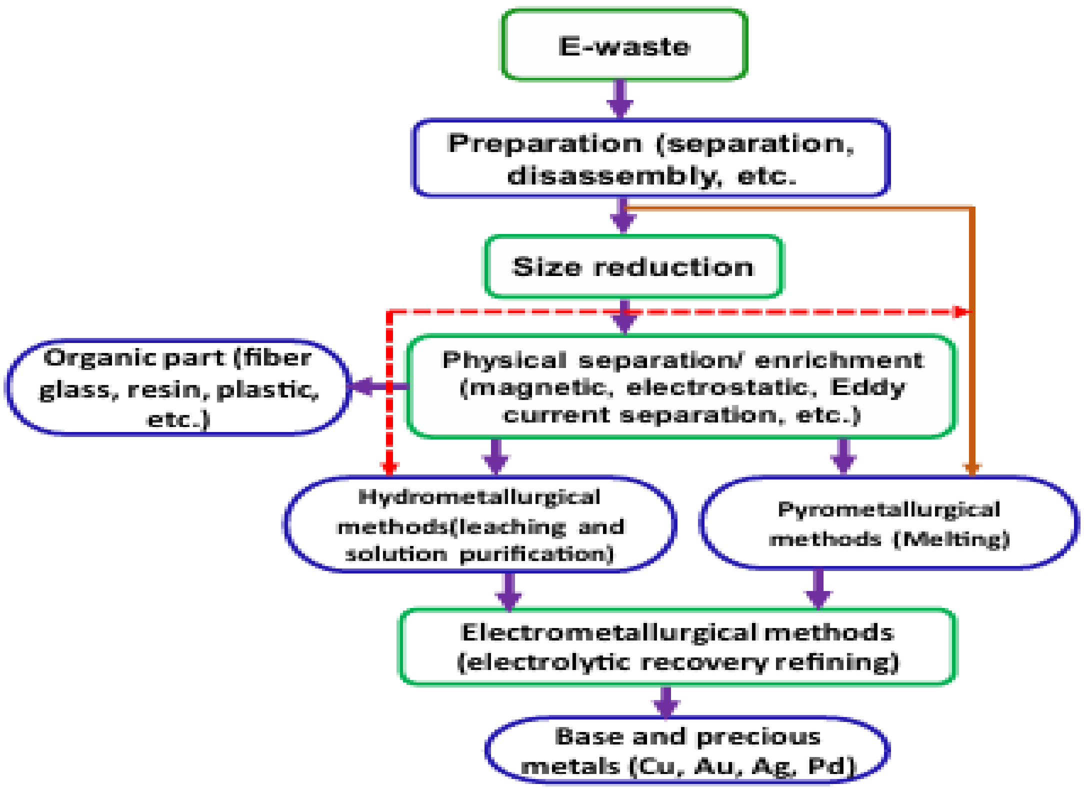

Figure 5. E-Waste Treatment Process. Source: Chancerel et al. (2009).

E. E-WASTE MANAGEMENT IN DEVELOPED AND DEVELOPING COUNTRIES

E-waste management varies across different countries worldwide, and this is highly correlated with the development level in this country. In more developed countries, recycling facilities can generally be categorized into two types based on the methods they utilize. The first type focuses on the physical disassembly and mechanical processing

of E-waste to extract raw materials, while the second type uses metallurgical processes to recover metals (Veit & Bernardes, 2015). In contrast are developing countries where most E-waste management is unregulated, with valuable materials frequently recovered in small-scale workshops using primitive recycling methods (Abdelbasir et al., 2018). While recycling costs are lower in backyard operations, which are common in developing countries, large-scale processes allow for significantly higher recovery rates of valuable materials, such as precious metals, compared to small-scale methods (Sepúlveda et al., 2010). Furthermore, in developing countries, informal E-waste recycling is associated with serious environmental pollution and workers' exposure to harmful chemicals derived from E-waste (Tsydenova & Bengtsson, 2011). Egypt is one of the developing countries in which the informal recycling of E-waste is the predominant recycling method. In 2019, approximately 1.1 million tons of EEE were introduced into the Egyptian market, resulting in the generation of 0.586 million tons of E-waste (Sakr et al., 2021). This positions Egypt as the largest market for electrical equipment and the leading generator of E-waste in Africa, as shown in Figure 6 (Sakr et al., 2021). As previously mentioned, E-waste recycling has both environmental and economic aspects. However, while economic growth and environmental protection often conflict, in Egypt, recycling is a developing industry and market that is primarily motivated by economic needs (Dahroug, 2010). The E-waste recycling system in Egypt relies on individuals such as collectors, traders, and recyclers, who each play a part. While the volume of E-waste continues to grow, investment in recycling activities, such as collection, dismantling, sorting, and recovery, remains limited. As a result, it has become a public challenge to various organizations, authorities, individuals, and small business owners to join this industry (El-Hadary, 2011). Despite the large amounts of E-waste produced annually, the formal sector collects and recycles only a small fraction, leaving most E-waste improperly treated or discarded. To date, neither the government nor the private-sector has implemented official E-waste management programs, with recycling activities predominantly handled through informal channels (Abdelbasir et al., 2018). The informal sector is known for gathering and moving E-waste, as well as extracting valuable materials and selling them to intermediary traders. It also sorts the E-waste into different categories and sells the items directly to recyclers, secondhand equipment shops, or other relevant buyers (Abdelbasir et al., 2018).

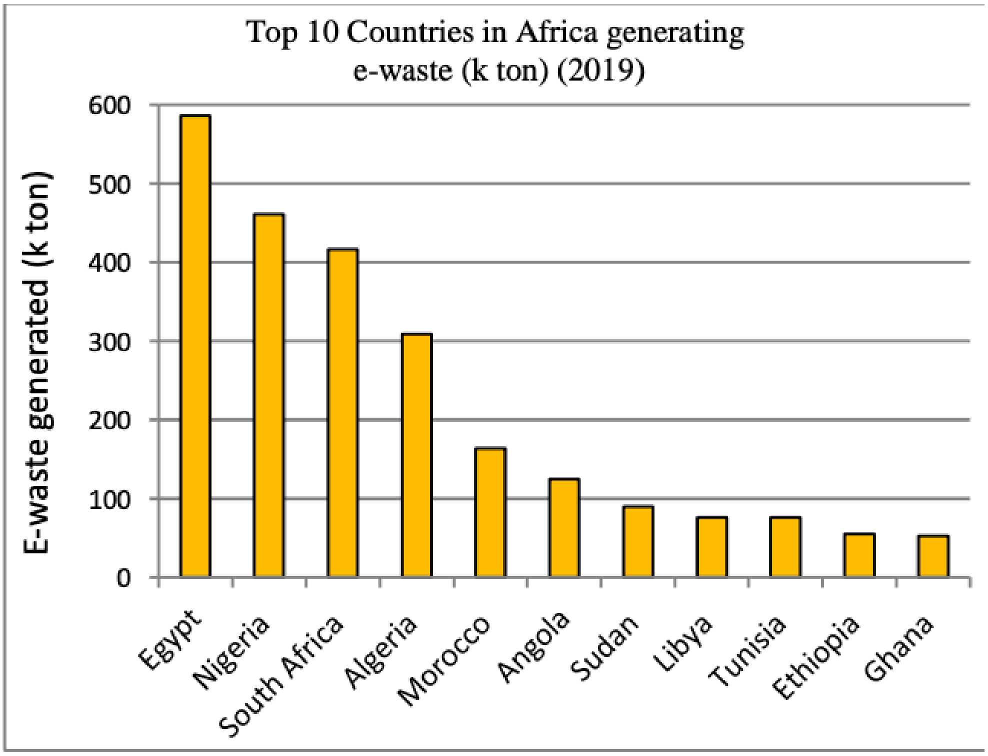

Figure 6. Leading Producers of E-Waste in Africa. Source: Sakr et al. (2021).

F. RECENT RESEARCH

Yang et al. (2021) explore the economic viability and environmental implications of E-waste recycling. They apply a CBA framework to evaluate the revenues, costs, and profits associated with E-waste recycling in three major regions: Europe, North America, and China. The study uses a five-stage framework to assess the costs and revenues of E-waste recycling, focusing on mobile phones and notebook computers as representative E-waste categories. These devices are chosen due to their high content of recoverable metals, such as gold, palladium, and copper. The research divides the recycling process into five key stages:

1. **Collection:** Gathering E-waste through formal or informal systems.
2. **Transportation to Dismantling Facilities:** Moving collected E-waste to processing sites.
3. **Manual Dismantling:** Breaking down devices into components, a process modeled using the Solve the E-Waste Problem (StEP) tool.

4. **Transportation to Metal Recovery:** Delivering dismantled components to facilities for metal extraction.
5. **Metal Recovery:** Extracting valuable metals using pyrometallurgical or hydrometallurgical methods (Yang et al., 2021).

Yang et al. (2021) estimate the energy required for metal recovery processes (pyrometallurgical and hydrometallurgical methods) and convert it into monetary costs based on electricity prices in the three regions studied, and then final profits are calculated by deducting energy and processing costs from total revenues. The study highlights the following key findings and introduces innovative policy recommendations to address global E-waste challenges.

1. Economic Potential of E-Waste Recycling

- Yang et al. (2021) emphasize the high economic value of recovering metals from E-waste, particularly from printed circuit boards (PCBs), which constitute only 3–6% of E-waste by weight but generate 40% of recycling revenue.
- The economic potential of one ton of E-waste can reach US$9,600 with a range between US$715,000 and US$929,000 (Yang et al., 2021).

2. Job Creation

- E-waste recycling has substantial potential for job creation. For instance, in China, the estimated job opportunities from recycling range from 1.81 to 2.03 million jobs per year, with similar but smaller scales in Europe and North America (Yang et al., 2021).

3. Environmental Impact

- Yang et al. (2021) highlight the need to address the environmental burden caused by informal E-waste recycling, particularly in developing countries, where toxic substances are often released into the environment.

4. Policy Changes

- Despite the economic potential of E-waste, only 20% of global E-waste was properly recycled in 2016, with the remainder either discarded in landfills or informally processed (Yang et al., 2021).
- Variations in policies and regulations across regions significantly impact recycling efficiency and profitability (Yang et al., 2021).

Yang et al. (2021) emphasize the urgent need for a global approach to E-waste management. Integrating CBA with innovative policy tools provides valuable insights into the economic, environmental, and social aspects of recycling. However, the authors highlight the necessity of more robust and localized data to improve the accuracy and applicability of their findings.

Additionally, a recently published case study, "E-Waste Management in India—A Case Study of Vizag, Andhra Pradesh" (Khanna & Das, 2022), presents the implementation of an E-waste recycling program in India. This program effectively conducts E-waste urban mining using a combination of manual, semi-manual, and automated techniques. Its aim is to maximize economic gains while minimizing environmental impact. The management process outlined in the case study begins with the ethical collection of E-waste from government and private-sector organizations. It involves implementing the appropriate mechanisms and processes to handle the waste, ultimately resulting in products that can be reused or providing a valuable supply of rare metals. This approach contributes to addressing the raw material availability challenges facing industrial sectors. The process of E-waste collection and management outlines is shown in Figure 7.

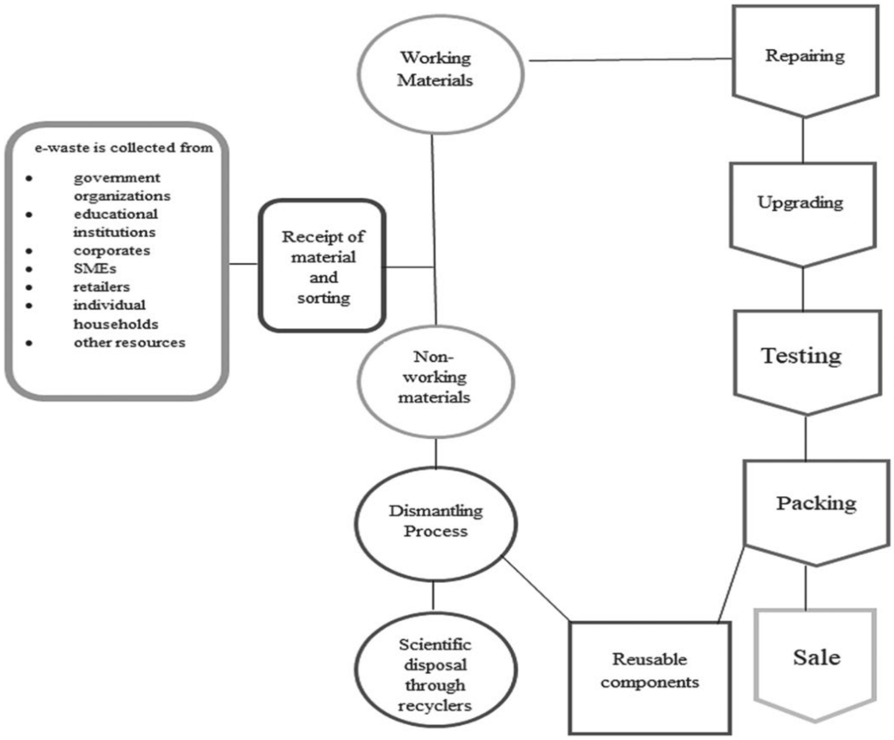

Figure 7. Process of E-Waste Collection and Management. Source: Khanna & Das (2022).

The concept adopted by this Indian firm represents a significant initiative aimed at establishing a formal and sustainable E-waste management process. Along with the government enforcement of rules and regulations for the proper handling and management of E-waste (Rajput, 2021), this approach serves as an excellent example of promoting E-waste management practices in developing countries to address the exponentially rapidly growing issue of E-waste accumulation worldwide.

In summary, this literature review has explored CEA as a methodology in evaluating alternatives without monetizing intangible benefits, which makes it a valuable tool for resource-limited environments like the Egyptian MOD. Lean thinking principles were examined as a valuable framework for enhancing the efficiency and effectiveness of E-waste processes. By identifying and eliminating waste, lean thinking offers practical tools for mapping and optimizing operations, making it a compelling approach for streamlining the MOD's E-waste management process. This literature also discusses the contrast between global practices in developed and developing countries and highlights the need for structured solutions in Egypt, where informal recycling dominates, as well as noting practices from previous research that discussed E-waste management in different countries. These insights set the stage for the next chapter in which these methodologies and concepts are explored further. This thesis applies the learned approaches to the current MOD E-waste process, aiming to make necessary modifications that will improve the system's efficiency and outcomes from an economic perspective.

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IV. ANALYSIS

This chapter presents an analysis of the Egyptian MOD's current approach to E-waste management and explores an alternative strategy focused on internal recycling by adopting an E-waste recycling plant within MOD. This chapter applies the frameworks discussed in the previous chapter—process mapping, CEA, lean thinking—to assess the economic efficiency of the MOD's current process in recycling E-waste. The analysis maps out the MOD's existing E-waste flow and compares the current model, which depends on selling the E-waste to private parties, with a proposed internal recycling plant, which is designed to maximize material recovery and increase profitability.

A. CURRENT PROCESS OF E-WASTE MANAGEMENT IN THE MOD

The Egyptian MOD, like many militaries worldwide, generates a significant amount of E-waste due to continuous upgrades of weapons and equipment in addition to maintenance of EEE. The MOD's current approach is selling the E-waste after collection to a third-party entity. The process starts at the unit level, where EEE that either has reached the end of its service life or needs maintenance is sent to intermediate-level warehouses and workshops. These facilities serve as a temporary storage and a repair hub to ensure that equipment is maintained and sent back for continued use or identified as no longer functional. The WEEE of the equipment that is beyond repair such as PCBs is separated and directed to the main warehouses and workshops. At this stage, all accumulated E-waste from various units and intermediate facilities is systematically gathered, which creates a centralized collection point for the MOD to ensure that large quantities of E-waste are processed together rather than in smaller batches. Then, every three months, the MOD organizes auctions to sell the collected E-waste to a third-party entity. However, due to the lack of a formal E-waste recycling industry in Egypt, the buyers in these auctions are primarily resellers rather than recyclers. Since large-scale, regulated facilities are scarce, these bidders do not process the WEEE domestically. Instead, the highest bidders acquire the E-waste and often export it outside Egypt to countries with an established recycling industry. This cycle is repeated every three months to ensure that accumulated E-waste from the MOD is cleared out. Figure 8 shows the process of E-waste handling within the

Egyptian MOD. While this process provides a structured method for E-waste disposal within the MOD, it has some inefficiencies. The absence of an internal recycling plant means that the MOD is forfeiting valuable materials embedded in WEEE, especially PCBs, such as copper, aluminum, gold, and other precious metals. Currently PCBs are sold in auctions at an average price of 100 EGP per kilogram, which is equivalent to US$2/kg, meaning that the MOD receives 100,000 EGP/ton (US$2,000/ton) (Moataz Ramadan, personal communication, March 3, 2025). By considering the value of the extracted materials from PCBs such as gold, silver, copper, and palladium, this selling price is significantly lower than the potential earnings if the Egyptian MOD recycled its E-waste internally.

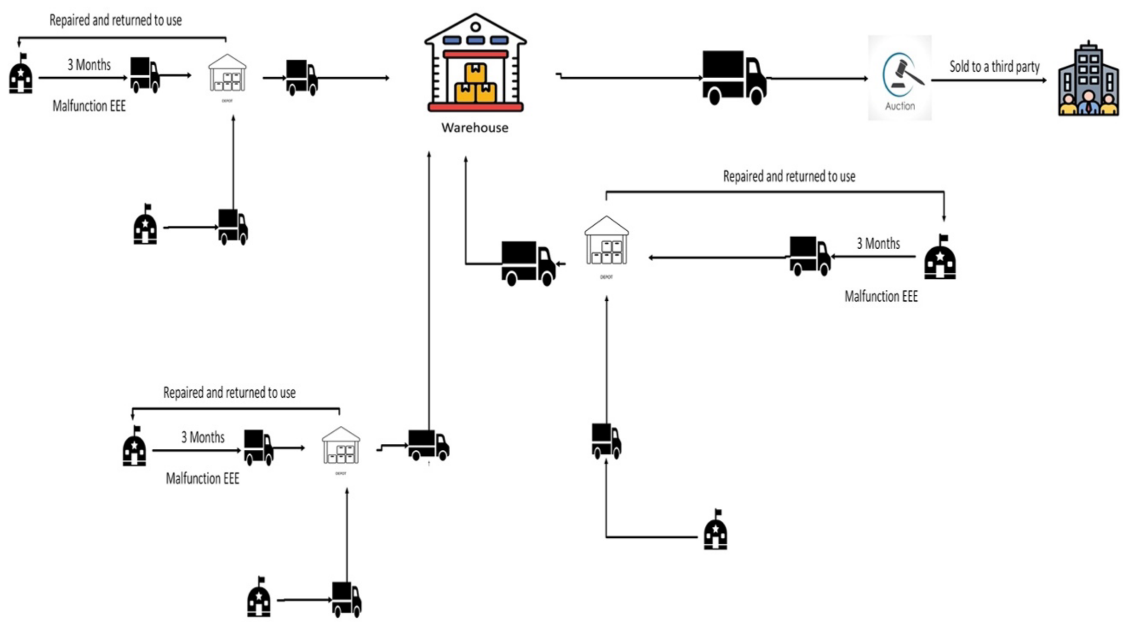

Figure 8. Current Process of E-Waste Recycling within the Egyptian MOD

B. PROPOSED E-WASTE EFFICIENT RECYCLING PLANT

The efficient recycling process for E-waste aims to maximize economic benefits while minimizing environmental impact. This process, often referred to as urban mining, involves extracting various minerals found in E-waste. This section focuses specifically on the recycling of PCBs as an example of urban mining. If conducted successfully, this process can recover valuable metals such as gold, silver, palladium, and copper, as well as non-metals like resin and fiber. The recovered metals and non-metals will help supply the industrial base in Egypt, particularly supporting the defense industrial sector by fulfilling part of their material needs.

Henan Zhengyang Machinery Equipment Co., Ltd. (Suny Group) is a Chinese machinery manufacturing enterprise, specializing in building PCB recycling plants (Suny Group, n.d.). The company offers a group of machines and equipment that are assembled to form a production line for recycling PCBs. Figure 9 shows the layout of a PCB recycling plant.

Figure 9. Henan Zhengyang, PCB Recycling Plant. Source: Suny Group (n.d.).

According to Suny Group (n.d.), the company offers PCB recycling plants comprising the following stages to perform the full urban mining process, including the following operations:

1. PCB components dismantling Machine exhaust processing system
2. Components screening machine
3. Components magnetic separator
4. AI components separating machine
5. PCB bare boards crushing and separating system
6. Surface gold stripping system
7. Precious metals recovery system

As outlined by Suny Group (n.d.), each part of this plant plays a role in the recycling process. It begins with dismantling the electronic components attached to the PCB and categorizing them by size for further processing. After all the components are removed from the board, the bare PCBs are introduced to a set of machinery that shreds, crushes, and grinds the boards. This process converts the PCBs into a fine powder, which contains a mixture of all the metal and non-metal components that make up the PCB.

Suny Group (n.d.) further explains that this powder mixture is then fed into the metal and non-metal separation machine, which employs magnetic separation using magnets to separate ferrous metals from non-ferrous materials and air classification separating materials based on their density using air flow. At this point, the outcomes of the physical recycling process are extracted as a segregated non-metal, typically fiber, resin, and a metal mixture resin powder.

According to Suny Group (n.d.), the recycling plant employs following processes:

- **Hydrometallurgy:** Using chemical solutions to dissolve and extract metals from PCB materials.
- **Electrochemical Process:** Applying electric current to deposit metals to electrodes to recover metals (e.g., gold, silver, and copper). The machines used to carry out these functions are the gold stripping machine, copper electrolysis system, and precious metals separating and refining machine.

As described by Suny Group (n.d.), the gold stripping machine is used to strip gold from various gold-plated scraps, such as waste phone circuit boards, central processing units (CPUs), and random access memory (RAM). With it, the gold recovery rate is as high as 99%, and high-purity gold can be obtained after further refining.

Suny Group (n.d.) also states that the disassembled electronic components, such as chips and north and south bridges, are baked with ozone. The residue is roasted with a soluble carrier, and the gold, platinum, and palladium are extracted by leaching the medium. Mixed metal powder can be refined using a copper electrolysis system, which provides copper with a purity of up to 99%. Figure 10 shows the mapping of the recycling plants' different processing paths for different types of metals extraction (Suny Group, n.d.).

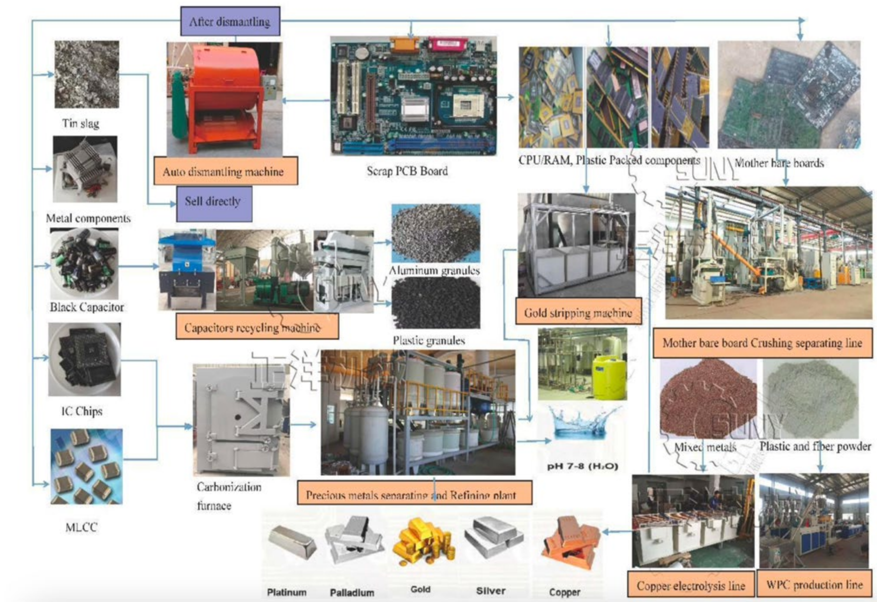

Figure 10. PCB Recycling Plant Metal Extraction Chart. Source: Suny Group (n.d.)

Hence, after demonstrating the technical properties and details of the recycling plant and aiming to implement this plant in the current E-waste management system in the MOD addressed earlier in section A, Figure 11 shows the modified process mapping after adding the PCB recycling plant into the existing MOD E-waste recycling process.

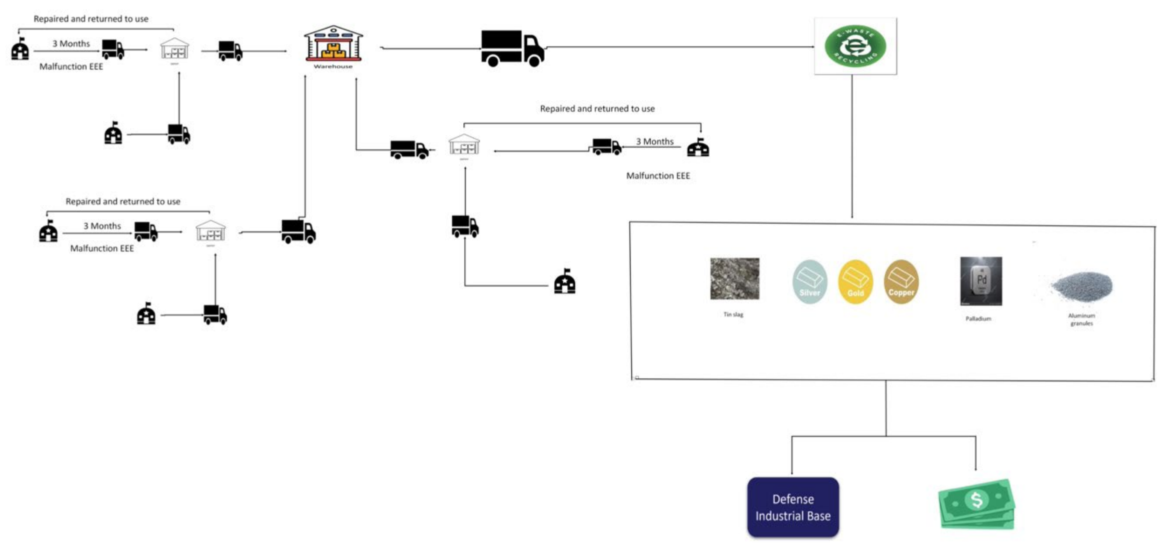

Figure 11. Proposed E-Waste Management Process in the Egyptian MOD

The next subsections introduce the estimated cost breakdown and profit analysis to enable better understanding of the investment estimation and payback cycle to address the economic benefits potential.

1. Cost of Recycling Plant Procurement

According to Wendy Dong (email to author, February 22, 2025), the full machinery of the PCB recycling plant equipment's Free on Board (FOB) price is $348,500, including all the processing stages needed for efficiently extracting all the metals. Table 2 shows the detailed equipment prices.

Table 2. Recycling Plant Machinery Procurement Cost. Source: W. Dong, email to author (February 27, 2025).

Processing	Machine/System	Total FOB cost (USD)
Physical	PCB components dismantling machine	$9,900
	Exhaust processing system for dismantling	$13,900
	Components screening machine	$1,600
Mechanical	Component magnetic separator	$3,300
	Mother bare boards crushing and separating system	$69,800
Chemical	Surface gold stripping Precious metals recovery system	$250,000
Total (USD)		$348,500

2. PCB Recycling Plant Direct Running Costs

The direct costs related to the recycling plant's operational cost (labor and power consumption) are associated with the labor workforce needed and the power costs to operate the full machinery and feed the PCB as it is broken down into different forms along the different stages of processing (physical, mechanical, and chemical). According to Suny Group (n.d.), the total power required to operate the proposed E-waste recycling plant is approximately 261.22 kW per hour, covering all machinery listed in Table 2. Based on the electricity rate of 1.94 EGP per kWh (Egyptian Electric Utility and Customer Protection, 2024), and assuming an operational schedule of eight hours per day, five days a week, the total monthly electricity cost is estimated at approximately 81,082 EGP, as shown in Table 3.

Table 3. Recycling Plant Machinery Power Consumption and Associated Costs in Egypt

Processing	Machine / System	Power (KW\h)	Power Cost (EGP\kWh)	Total Cost (EGP\kWh)	Total Power Cost (EGP) (160 h/month)
Physical	PCB components dismantling machine	3.37	1.94	6.5378	1046.04
	Exhaust processing system for dismantling	8.5		16.49	2638.4
	Components screening machine	0.55		1.067	170.72

Mechanical	Component magnetic separator	1.25		2.425	388
	Mother bare boards crushing and separating system	154.9		300.506	48080.96
Chemical	Surface gold stripping Precious metals recovery system	92.65		179.741	28758.56
Total (EGP)		261.22		506.7668	81083
Equivalent USD (with exchange rate $1=50 EGP)					$1622

The operation of the recycling plant requires a direct labor force of 15 workers. This estimate is based on the number of machines and their respective feeding types (manual, semi-automatic, or fully automated) (Wendy Dong, email to author, February 27, 2025). As the average monthly wage in Egypt is 14,317 EGP (remote people, 2025), the total monthly labor cost is approximately 214,755 EGP, which is equivalent to US$4,295, Table 4 shows the recycling plant labor costs in Egypt.

Table 4. Recycling Plant Labor Costs in Egypt

Processing	Machine / System	Labor Workforce	Average Wage / Month	Total Labor Cost / Month
Physical	PCB components dismantling machine	15	14317 EGP	214755 EGP
	Exhaust processing system for dismantling			
	Components screening machine			
Mechanical	Component magnetic separator			
	Mother bare boards crushing and separating system			
Chemical	Surface gold stripping Precious metals recovery system			
Equivalent (USD with exchange rate $1=50 EGP)				$4295

In addition to labor costs, the gold recovery process involves material expenses. As noted by Wendy Dong (email to author, February 27, 2025), 1 kg of stripping chemicals—costing $100—can extract approximately 200 to 250 grams of gold.

Maintenance and repair costs are critical to consider when evaluating the costs associated with implementing the E-waste recycling plant. Maintenance and repair expenses for an E-waste recycling facility typically depend on factors such as the scale of operations, system complexity, and the equipment's age and condition. On average, companies in this sector generally allocate around 5% to 10% of their overall operating budget (Shekin, 2025).

3. Collection and Transportation Costs

In general, these costs vary depending on of the distance between the warehouses and depot facilities that the plant will serve to collect and store their E-waste before conducting the recycling processes. In general terms, the cost for transporting a 20-foot container by road from Cairo to Alexandria (220 km = 137 miles) in Egypt typically ranges between EGP 3,000 and EGP 5,000, which is equivalent to $100 (Globy, n.d.). For ease of calculation, assume that a 20-foot container carries 1 ton of E-waste from the warehouses to the recycling plant.

4. Facility Space Requirements and Leasing Costs

An E-waste recycling plant requires adequate place to accommodate machinery, material flow, storage area, and administrative functions. As a general guideline, a recycling facility with a processing capacity of 1 ton per day should have at least 500 square meters of space. However, preference for authorization is often given to recyclers operating at a minimum capacity of 5 tons per day, provided they have a facility spanning approximately 2,500 square meters (GIZ GmBH, 2022). The average leasing cost for an industrial facility in Egypt based on current market estimates is about 650,000 EGP per month, which is equal to 7,800,000 EGP per year ($156,000).

5. PCB Recycling Revenues from the Extracted Metals

In general, the expected quantities of metals that can be extracted from the recycling process of each ton of PCBs may vary depending on the type and size of the PCBs being recycled (Veit & Bernardes, 2015). The expected amount of extracted minerals from recycling one ton of FR4 PCBs from laptops, computers, and cell phones at Henan's recycling plant is listed in Table 5 (Wendy Dong, email to author, February 27, 2025). Additionally, the plant has a processing capacity of up to 5 tons per day. The company recommends operating the plant at its daily capacity of 5 tons to maximize return on investment (Wendy Dong, email to author, February 27, 2025). This includes purchasing a complete range of mining equipment, which encompasses mechanical, chemical, and smelting tools necessary for the recycling process.

Table 5. The PCB Recycling Plant Metals Extracted Amounts

Metals	Content/T	Total Extracted Metal Content / 5T PCB Recycling	Unit Price per Weight Unit (g – kg)		Extracted Metal Total Price / 5T PCB Recycling	Metal Recovery Rate
			(EGP)	(USD)		
Ag	118g/t	590 g	EGP 4,873.66	$97.47	$57,509	99%
Au	731g/t	3655 g	EGP 55.07	$1.10	$4,026	99%
Pd	19g/t	95 g	EGP 1,558.54	$31.17	$2,961	98%
Cu	30%	1500 kg	EGP 551.17	$11.02	$16,535	99%
Ni	0.23%	11.5 kg	EGP 827.52	$16.55	$190	90%
Pb	3%	150 kg	EGP 105.08	$2.10	$315	90%
Sn	3.60%	180 kg	EGP 1,782.35	$35.65	$6,416	90%
Al	2.04%	102 kg	EGP 135.90	$2.72	$274	99%
Total income					$88,227	

The quantities of extracted minerals given by the company generally match with the numbers stated in recent research concerned with investigating the economic benefits of recycling cell phones PCBs (Veit & Bernardes, 2015).

C. MEASUREMENTS OF EFFECTIVENESS

The potential economic improvements of the proposed E-waste management process, as discussed in the previous section, are accompanied by qualitative measures of effectiveness. These measures focus on the environmental impact, adherence to efficient disposal standards for EEE, and the outcomes of E-waste recycling, which can supply the defense industrial base in Egypt with raw materials. Incorporating these measures will enhance the analysis of this research, demonstrating the effectiveness of the proposed E-waste management process.

1. Environmental Impact

The proper management of E-waste involves implementing environmentally friendly extraction methods to reduce the release of hazardous substances and prevent improper disposal in landfills or waterways. Such practices are essential for protecting the environment and minimizing risks to human health (Andersen, 2025). Currently, the MOD process concludes with the sale of E-waste to private-sector companies. However, this does not guarantee that WEEE will be disposed of correctly. Many of these companies lack the necessary recycling facilities to handle E-waste properly. As a result, they may engage in unmonitored processing to recover valuable materials, which can lead to harmful environmental practices, such as burying the remaining waste in landfills. Furthermore, they may resell or export E-waste to neighboring countries that possess appropriate recycling facilities.

To address these issues, conducting the recycling process internally within the Egyptian MOD would ensure proper and efficient disposal of E-waste. This approach would help mitigate environmental risks and safeguard human health both in the short- and long-term.

2. Compliance with E-Waste Recycling Standards Measure

Recently, the Egyptian government has been working to address the risks associated with E-waste and its hazardous materials, which have a devastating impact on the environment. While environmental legislation and laws designed to ensure proper E-waste management in Egypt have not yet been fully implemented, the Egyptian Ministry of Environment is actively involved in developing legislative sections that will comprehensively detail the E-waste management process. This effort aims to mandate proper and sustainable practices for the disposal of EEE (Lotfy, 2024) .

Furthermore, the current state of E-waste management in the Egyptian MOD does not require any costs or investments because the responsibility for recycling has been transferred to private-sector companies that purchase the MOD's E-waste. However, this process lacks reasonable assurance that E-waste disposal complies with international standards issued by the UNU (Forti et al., 2020) and wastes the economic potential of extracting.

In contrast, implementing the proposed E-waste process within the Egyptian MOD would place the compliance responsibility and cost burden on the MOD, which increases the operational obligations.

3. Supply Minerals for Defense Products Manufactured in Egypt

The metals extracted from E-waste recycling plants, as proposed, have the potential to provide a reliable supply of raw materials for the Egyptian defense industrial base (DIB), which is essential for manufacturing defense products. By utilizing these extracted minerals from E-waste, the MOD can bolster the DIB, reduce reliance on imported materials, and promote sustainable practices.

For instance, in the manufacturing of secure communication devices, gold and silver are utilized in the circuitry, ensuring reliable and efficient performance. Additionally, in the production of military vehicles and ammunition, copper and aluminum are used in the electrical systems and structural components, enhancing both performance and durability.

Currently, these potentials cannot be demonstrated because the metal extraction process occurs outside of the MOD premises and is beyond our control.

D. PCB RECYCLING (CURRENT VS. PROPOSED) PROCESS COSTS AND EFFECTIVENESS COMPARISON

The previous sections outlined the main costs and investments required to implement the proposed E-waste recycling process at the Egyptian MOD. Additionally, the effectiveness measures discussed in the previous sub-section are summarized in Table 6.

Table 6. Cost and Effectiveness Measures of the Status Quo and the Proposed E-Waste Management Process

Aspect	Implementing a PCB Recycling Plant	Selling E-Waste Unrecycled
Initial investment for equipment procurement	$348,500	Minimal (collection and transportation costs)
Annual operating costs	Labor cost = $51,541 (Required labor = 15 personnel) Utilities = $19,460 Building lease = $156,000 Chemical consumables = $72,000 Maintenance = $34,850 Transportation = $120,000	Labor cost = $17,180 (Required labor = 5 personnel) Transportation = $120,000
Total costs	$802,351	$137,180
Recovered metals annual revenues 1200 Ton PCB / Year	$21,174,408	$2,400,000
Profits	$20,372,057	$2,262,820
Environmental impact	- Environmentally friendly process - Eliminate hazardous materials' impacts on the environment	- Buyers may use informal or unsafe recycling methods

Aspect	Implementing a PCB Recycling Plant	Selling E-Waste Unrecycled
		- Potential soil and waterways contamination by hazardous materials
Compliance with international standards	- MOD has responsibility for regulatory compliance	- Uncertainty about adherence to international standards - Responsibility transferred to buyers
Supply basic minerals to the Egyptian DIB	- Strengthens strategic self-sufficiency - Support local production of defense products	- No contribution to DIB - MOD loses potential strategic materials

Table 6 makes clear the significant improvement of the revenues realized by implementing the proposed process for E-waste Management. The high profit margin achieved from recycling 1,200 tons of E-waste in Egypt is driven by the low costs of labor, utilities, and transportation. Moreover, the expected annual operating costs needed for the E-waste recycling are paid in Egyptian pounds while the value of recovered minerals such as gold, silver, copper, and palladium is based on international market prices, which are valid in most countries globally, including Egypt. With a focused view on the results, the currency exchange between USD and EGP is also a basic driver for high profitability.

To compare the current E-waste disposal process with the proposed recycling process, several key MOEs have been evaluated. These include profitability, environmental impact, regulatory compliance, and support for the defense industrial base. A qualitative ranking system was used, where 1 indicates a more favorable outcome and 2 indicates a less favorable one, based on what has been discussed in the previous section. While the proposed recycling process scores better in most categories, the current approach ranks higher in regulatory compliance due to the transfer of legal compliance responsibility to private parties. Table 7 shows this qualitative assessment.

Table 7. Cost-Effectiveness Comparison

Process type	Cost	Profit	Environmental impact	Regulatory compliance	Supplying DIB
Current process	1	2	2	1	2
Proposed process	2	1	1	2	1

Figure 12 provides a visual cost-effectiveness comparison between the current E-waste disposal process and the proposed recycling process, using a qualitative understanding of cost and effectiveness. While the graph does not represent precise numerical values, it reflects the relative positioning of both options based on qualitative rankings across MOEs. The proposed process, while higher in cost, demonstrates significantly greater overall effectiveness. In contrast, the current process has a lower cost but also a lower effectiveness.

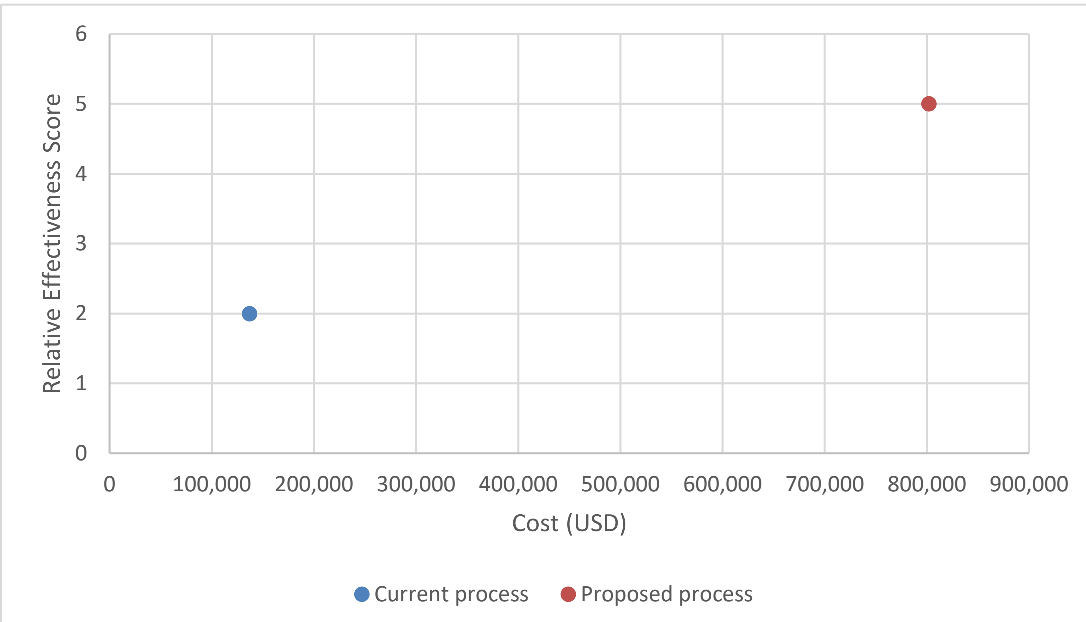

Figure 12. Summary of Cost-Effectiveness Comparison

E. APPLYING LEAN THINKING TO IMPROVE THE PROCESS

Lean thinking, as discussed in the previous chapter, is focused on eliminating waste, improving efficiency, and maximizing value. Applying lean thinking to E-waste recycling in Egypt's MOD can streamline processes, reduce unnecessary steps, and increase the recovery of valuable materials.

1. Identifying Value in the MOD's E-Waste Recycling Process

- Maximizing financial recovery from E-waste by extracting high value-materials (gold, silver, copper) instead of selling mixed waste at a lower price.
- Reducing storage and handling costs through an efficient disposal system.

- Enhancing sustainability and minimizing environmental harm by ensuring hazardous components (batteries, mercury, lead) are properly treated.
- Improving inventory efficiency by implementing a structured recycling plant in the MOD's recycling system.

2. Lean Value Stream for MOD E-Waste Recycling

- Military units send their retired demilitarized equipment and equipment that needs maintenance to the intermediate-level warehouses.
- Intermediate-level warehouses conduct sorting of E-waste and categorize it into high value items such as PCB, and hazardous waste such as lithium-ion batteries.
- E-waste then is sent directly to the recycling plant.
- Recovered materials (gold, silver, copper) are either reused in MOD's industrial base or sold at market value.

3. Creating Flow and Reducing Bottlenecks

- Implement a continuous disposal and recycling schedule instead of waiting for bulk accumulation to reduce storage bottlenecks.
- Training personnel in standardized dismantling techniques to improve efficiency.

4. Continuous Improvement for MOD's Recycling System

- Conduct regular audit reviews of recycling to identify inefficiencies and then adjust workflows.
- Train recycling plant personnel in lean practices and encourage feedback to improve the process.
- Continuously assess and adopt advanced recycling technologies to improve material recovery rates and reduce waste.
- Establish key performance indicators such as processing time and material recovery rates and track them to ensure continuous refinement.

This chapter examined the current process that MOD follows in handling E-waste, particularly PCBs, and compared it with the proposed in-house recycling system. It outlined the plant's power requirements, labor needs, associated operating costs such as transportation and maintenance, and expected material recovery. The analysis weighed the financial implications of continuing the current resale model versus investing in internal recycling. This chapter also applied lean thinking to the new system, highlighting how wastes can be reduced and how the process flow could be improved.

V. RECOMMENDATIONS AND CONCLUSION

After the analysis presented in Chapter IV for the proposed E-waste management process within the Egyptian MOD, this thesis identified both advantages and disadvantages. It is clearly shown that the current approach results in wasted resources and poses environmental hazards.

The next step is to present the findings of this study and introduce it to the MOD decision-makers to secure approval for the necessary investment to implement the proposed process. This will involve starting the procurement process for the recycling plant equipment, developing the required infrastructure, and training the workforce within the Egyptian MOD on how to use the equipment and carry out the E-waste recycling procedures. The following sections of this chapter elaborate on these points and provide recommendations for future work related to this thesis study.

A. RESEARCH FINDINGS AND RECOMMENDATIONS

The findings of this research highlight the significant potential of establishing an internal E-waste recycling system within the Egyptian MOD, especially considering global raw material demand and the undervaluation of E-waste under the current auction model. By shifting from selling E-waste to recycling it internally to extract valuable metals such as gold, copper, and aluminum, the MOD will generate substantially higher financial returns while also contributing to environmental protection and strategic autonomy. Additionally, internal recycling can serve the Egyptian DIB by supplying critical raw materials, reducing dependency on foreign inputs, and enhancing operational readiness. However, these advantages do not come without trade-offs. Implementing such a system requires significant capital investment and ongoing operational costs including labor, maintenance, electricity, and chemical inputs. Furthermore, the MOD would have full responsibility for regulatory compliance, environmental safety, and technical oversight, burdens that are currently the responsibility of private buyers under the auction system. This transition would also introduce new logistical and administrative complexities that the current model avoids. Despite these challenges, the long-term strategic, financial, and environmental benefits justify the investment, particularly when implemented in a phased, well-planned manner that allows for adaptation and learning. Ultimately, this internal recycling process offers the MOD an opportunity to align resource recovery with national defense objectives, promote sustainable practices, and reclaim the hidden value currently lost through third-party disposal.

1. Adopt a Phased Implementation Plan

The Egyptian MOD could first implement a small-scale internal plant focusing on recycling E-waste from PCBs rather than launching a full-scale facility. This approach would allow the MOD to observe and evaluate the system's actual performance under real operating conditions. By starting on a limited scale, the MOD could assess material recovery rates, identify operational challenges, and make informed adjustments before committing to full expansion. This strategy would help reduce the financial risk while building the internal knowledge of how to operate an E-waste recycling plant.

2. Establish Training and Workforce Readiness

The success of the E-waste recycling plant implementation will depend on not only the technology but also the workforce operating it. Therefore, the MOD should establish a structured training program that focuses on safe dismantling practices, materials handling, environmental protection control, and lean operational strategies. Personnel should be equipped with both technical knowledge and an understanding of regulatory frameworks to ensure compliance with national laws. Additionally, developing a skilled internal workforce would reduce dependency on external consultants and improve the long-term resilience and efficiency of the program.

3. Leverage Recovered Materials Strategically

The MOD should establish a policy that ensures that the recovered materials are redirected first to the Egyptian DIB to assess their suitability and necessity for defense production. Only materials that are not required internally should be sold on the market. This approach ensures that strategic materials are retained for critical defense applications. By integrating this step into the recycling process, the MOD could strengthen supply chain resilience and ensure that the economic gains from recycling directly support national defense capabilities.

B. RECOMMENDED FUTURE RESEARCH

This study provides a CEA of an internal E-waste recycling system within the Egyptian MOD, using qualitative MOEs. Future research should aim to expand on these findings through more quantitative data and operationally grounded approaches. Researchers are encouraged to develop a fully quantitative framework for measuring MOEs, allowing for clearer comparisons between alternatives. Once the proposed system is implemented and operational data becomes available, future studies can also apply lean thinking principles more rigorously. This would involve identifying actual bottlenecks, inefficiencies, and types of waste that emerge during day-to-day operations and using real-time insights to refine the process. By building on both the lessons learned in this study and the real-world experience that will follow once the system is implemented and running, future researchers can offer more grounded, practical recommendations. This would help make E-waste management in the MOD not just more efficient but also better aligned with on-the-ground realities and national priorities.

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