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Dynamic Business Modelling for Sustainability Adapted Version of Implementation for Social Sustainability

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ABSTRACT

In the last decade, both sustainability and business models for sustainability have increased in importance. Sustainability issues have become the focus of discussion. These issues are interlinked and often negatively impact each other. They are complex and include socio-ecological dilemmas, exist in almost every aspect of our society (economic, environmental, social), and are hard to formulate. They may have multiple, incompatible solutions, competing objectives, and open timeframes. Previous research has not developed satisfactory ways to comprehend and solve problems of this nature. Life Cycle Assessment (LCA) the widely used method to assess sustainable development has reached its limitation to achieve sustainable social goals. System Dynamics (SD) is a valuable methodology that enhances understanding of the structure and internal dynamic behaviours of large, complex, and dynamic systems, leading to improved decision-making. It offers a philosophy and set of tools for modelling, analysing, and simulating dynamic systems. This research applied system dynamics methods in conjunction with simulation software to assess the potential impact of a solution on environmental, social, and economic aspects of a complex system, aims to gain insights into the system's behaviour and identify the potential consequences of interventions or policy changes across multiple dimensions. This paper responds to the urgent need for a new business model by presenting a concept for an adapted dynamic business modelling for sustainability (aDBMfS) using system dynamics. Case studies in the smartphone industry are applied.

Keywords*—Adapted business models design for sustainability (aDBMfS); sustainability; system dynamics modelling; social life cycle sustainability assessment (SLSA); social life cycle assessment integration into PLM System*

I. Introduction

Given the growing significance of sustainability over the past decade, research on business models for sustainability (BMfS) has emerged as a central focus across various sectors of society, including the economic, environmental, and social domains [1]. Researchers addressed topics such as how to make a supply chain sustainable and how to use system dynamics methods to analyse sustainability issues in the smartphone lifecycle.

A. *Sustainability Issues in the Smartphone Lifecycle*

The sustainability issues in the smartphone lifecycle's different phases are identified by Zufall et al. [2] as follows:

- During the resource extraction and processing phase:
  - Illicit operations and sourcing of hazardous or conflict minerals
  - Poor working conditions, including child and forced labour, and excessive working hours
  - Environmental degradation resulting from mining and processing, such as high land use and soil contamination
- In the design and manufacturing phase:
  - Energy and resource-intensive manufacturing processes
  - Poor working conditions, particularly in proprietary and non-reparable systems

- In the distribution and network provision phase:
  - Transport emissions
  - Fast replacement business models that accelerate device replacement
- During the usage phase
  - Short average operating lifetime of devices
  - High electricity consumption
- In the end-of-life phase:
  - Stockpiling of functional devices that hinder reuse
  - Stockpiling of defective devices, preventing proper recycling
  - Illicit importation of electronic waste into emerging countries
  - Informal recycling sector deals with valuable materials
  - Poor working conditions in the recycling sector
  - Environmental pollution and health issues are caused by toxic substances in discarded electronics.

Zufall et al. also identified seven sustainable business model patterns to cover different lifecycle phases[2]. This paper focuses on the first pattern, "Sustainable Resource Company," during the "Resource Extraction" and "End-of-Life" phases (see the dashed labelling in Fig. 1). Social sustainability issues like child labour, poor working conditions, low wages, pollution, and occupational health problems caused by toxic materials in e-waste occurs mainly in these two phases. Our study applied system dynamics methods with simulation software to determine how a solution applied to a complex system would impact environmental, social, and economic aspects.

B. Characteristics of Social Life Cycle Sustainability Issue

Key characteristics of the lifecycle sustainability problem:

- Complexity
- Many variables
- Strong cross-coupling
- Nonlinear behaviour over time

Sustainability calls for balancing the environment, society and economy over time.

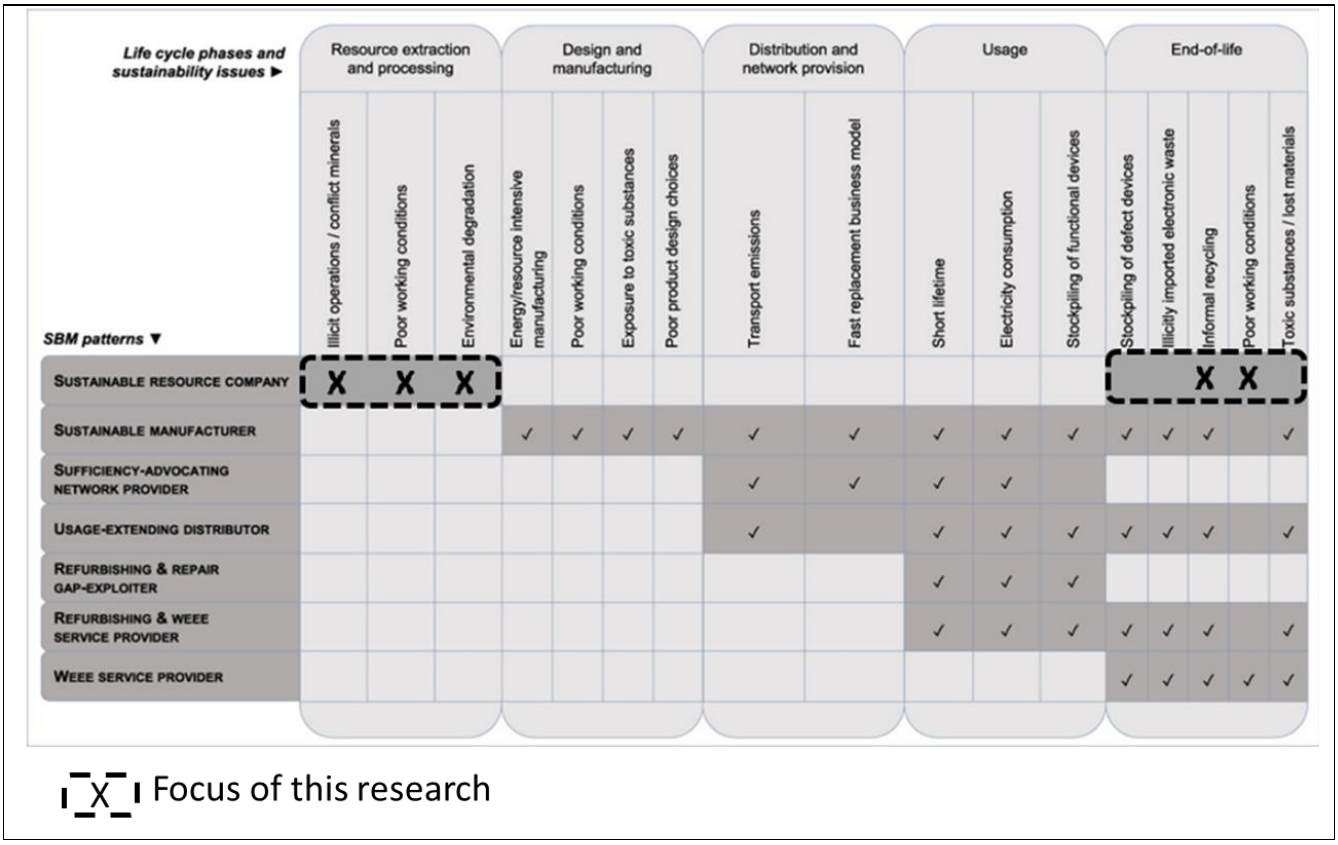
C. Research Methods

When selecting the research method(s) for this study, it is important to take the following considerations into account:

- Is the study empirical, interpretive, or a combination of both?
- The specific application areas of the research, such as the industry sector.
- The sustainability dimension is being addressed, which could involve one or more of the threedimensions of LCA.
- The type of case study, whether it is a full case study or a numerical example.
- The availability and extent of data collected for the case study, including the use of real data.
- The integration of different elements within the research.

In summary, this research applied the following methods: a mix of empirical & interpretive studies, with a smartphone as a case study from an electronic & electrical brunch. The data collected for the case study are real data or at least statistical data.

The research focused on the integration of SLCA (the social aspect of sustainability) into PLM or material lifecycle.



SBM patterns ▼ / Life cycle phases and sustainability issues ►	Resource extraction and processing			Design and manufacturing				Distribution and network provision		Usage			End-of-life				
	Illicit operations / conflict minerals	Poor working conditions	Environmental degradation	Energy/resource intensive manufacturing	Poor working conditions	Exposure to toxic substances	Poor product design choices	Transport emissions	Fast replacement business model	Short lifetime	Electricity consumption	Stockpiling of functional devices	Stockpiling of defect devices	Illicitly imported electronic waste	Informal recycling	Poor working conditions	Toxic substances / lost materials
SUSTAINABLE RESOURCE COMPANY	X	X	X												X	X	
SUSTAINABLE MANUFACTURER				✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
SUFFICIENCY-ADVOCATING NETWORK PROVIDER								✓	✓	✓	✓						
USAGE-EXTENDING DISTRIBUTOR								✓		✓	✓	✓	✓	✓	✓		✓
REFURBISHING & REPAIR GAP-EXPLOITER										✓	✓	✓					
REFURBISHING & WEEE SERVICE PROVIDER										✓	✓	✓	✓	✓	✓		✓
WEEE SERVICE PROVIDER													✓	✓	✓	✓	✓

X Focus of this research

Fig 1. Lifecycle sustainability issues along the smartphone lifecycle and the research focus.

D. Research Framework

This paper presents a dynamic business framework for sustainability research, which is an adaptation of Design Business Modelling for Sustainability (aDBMfS). The objective of this paper is to develop a descriptive model to explore and gather empirical data related to these inquiries. Whenever possible, established techniques, methods, and frameworks were incorporated. To evaluate the modelling approach and establish how to incorporate BMfS elements into a systemic structure, a case study was conducted, as depicted in Fig. 4, to provide an example of applying aDBMfS to analyse cobalt usage and its relevant issues (e.g., child labour) in the lifecycle of a smartphone.

E. Structure of this Paper

The next chapters are structured as follows:

- Section II: System Dynamics Method and Modelling
- Section III: Dynamic Business Modelling Framework
- Section IV: a Case Study with Smartphone
- Section V: Conceptual Modelling and Developing Causal Loop Diagram
- Section VI: Modelling with Simulation Software
- Section VII: Summary of Research Results
- Section VIII: Conclusion and Future Work

II. System Dynamics Method and Modelling

A. System Dynamics Method

SD is a methodology for analysing complex systems and problems over time with the aid of computer simulation software [3]. It handles complex systems in different domains. SD steps include making a loop diagram, connecting the variables, and documenting the relationships among them (direct or inverse). SD can identify interactions among related components in a system, improve communication and enhance decision-making policies in different scenarios. The modelled systems could be socio-economic, financial, climatic, or physical. SD models consist of only a few basic types of variables which are used to construct stock and flow diagrams with feedback loops and delays [4].

SD also helps to solve quantitative problems. Its simulation and the causal mechanisms (which analyse behaviour over time) can usefully be seen as generating those behaviours. In addition, SD involves feedback mechanisms such as causal links, feedback loops, stocks and flows and guiding policy structures within a causally closed boundary.

B. System Dynamics Model

In his book Industrial Dynamics, Jay Forrester [5] presented a type of model structure. He indicated the following characteristics which a model should have:

- Be able to have the capability to depict any cause-effect relationships in the desired statements.
- The mathematical nature should be straightforward.
- The nomenclature should align with industrial, economic, and social terminology.
- It should be scalable to accommodate a vast array of variables (thousands) without surpassing the practical limitations of digital computers.
- The ability to handle "continuous" interactions implies that the results will remain unaffected by artificial discontinuities caused by solution-time intervals. However, the model should still be able to generate abrupt changes in decisions when necessary.

C. System Dynamics Modelling Process

As per Nabavi, SD serves as an effective instrument for comprehending dynamics, particularly feedback mechanisms, within various social-ecological systems aiming for sustainable trajectories. In conjunction with quantitative simulations and optimization packages, SD provides qualitative tools (such as system archetypes, Causal Loop Diagrams, and Stock and Flow Diagrams) that augment understanding [6], see Fig. 2.

SD has the versatility to be applied in both qualitative and quantitative modelling. Qualitative modelling, also known as "soft operational research" or problem structuring method, can readily incorporate important tools and methods available within SD. On the other hand, quantitative SD modelling shares several similarities with traditional simulation methods and quantitative operations research tools. These similarities include factors like being empirically driven, undergoing thorough testing, and placing significant emphasis on output analysis. While traditional stocks and flows are fundamental components in quantitative SD modelling, they align with the principles and techniques employed in traditional simulation methods and quantitative operations research tools [7].

Dynamic systems theory emphasizes a process-oriented worldview, where processes are understood as interconnected patterns of change that unfold over time. These processes possess properties that can be described using a state space or a network. However, these properties are inherently dynamic and temporal, thus requiring the inclusion of time in their conceptualization. Stability, in this context, refers to a process consistently reproducing its properties over time, resulting in them remaining essentially unchanged for practical purposes [8]. Both qualitative and quantitative SD thinking, and modelling practices consider the extent of dynamic processes [6].

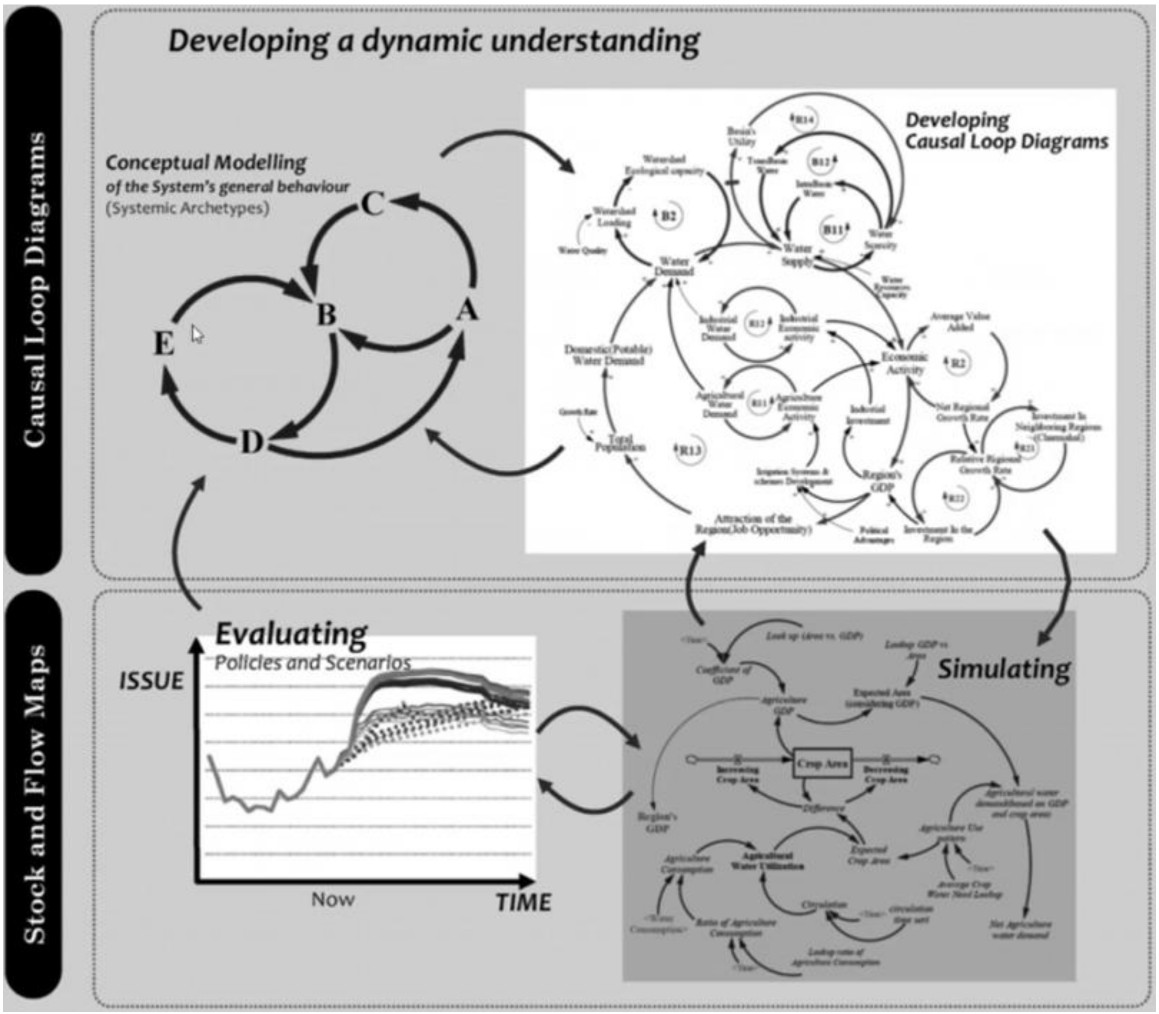


Fig.2. Developing a dynamic understanding [6].

For qualitative SD modelling, the process starts with problem definition, formulating a complex dynamic problem; followed by identifying key variables, and recognition of important factors that contribute to the problem. The last step is generating causal-loop (feedback) diagrams, identifying cause-and-effect relationships between the variables.

In quantitative SD, modelling will start with stock and flow diagrams, and identify the accumulations and rates of changes within the system. Model equations are applied to represent the causal relationships in a simple mathematical way. Then the simulations can be executed to model the behaviour over time. The last step is the model validation, testing and policy implementation, which compares the real and simulated behaviour, model structure, scenario analysis, testing policy alternatives and implementing changes in the real system that alleviate the problem.

III. DYNAMIC BUSINESSMODELLING FRAMEWORK

Cosenz et al. [1] proposed a dynamic business modelling for a sustainability approach that combines an adapted sustainable business model canvas and system dynamics modelling. They also reviewed the state of the art in Design Business Modelling for Sustainability (DBMfS) design tools, but no simulation is available based on this framework.

Lin et al. [9] applied this framework DBMfS developed by author Cosenz and enhanced it as adapted DBMfS. Fig. 3 shows the adapted sustainable business model canvas, which applies the DBMfS framework, to analyse extended LCA sustainable issues. Life cycle sustainability assessment issues have been already described by Lin et al., in the paper "Dynamic Business Modelling for Sustainability: Exploring a System Dynamics Perspective to Integrate Social Life Cycle Sustainability Assessment" [9].

Lin et al. [9] enhanced the DBMfS framework by applying it to the whole material lifecycle, which extends the product lifecycle.

- Applied system dynamic simulation tool (STELLA®) to DBMfS, to analyse the complex social problems.
- Applied DBMfS to sustainability modelling and its simulation implications on sustainability related to the smartphone market.
- Applied real data or statistical data from the smartphone industry to simulate cobalt's whole lifecycle.

Fig. 4 shows how the adapted Model – aDBMfS can be applied to cobalt usage in a smartphone lifecycle. Elements of this model outline how an organization operates in achieving both sustainability and viability goals. They are (a) key stakeholders, (b) strategic resources, (c) value proposition, (d) key processes, (e) customer segments, (e) social value, (f) economic value, and (g) environmental value.

Here, EBIT stands for earnings before interest and taxes; NGO is the abbreviation of a non-governmental organization.

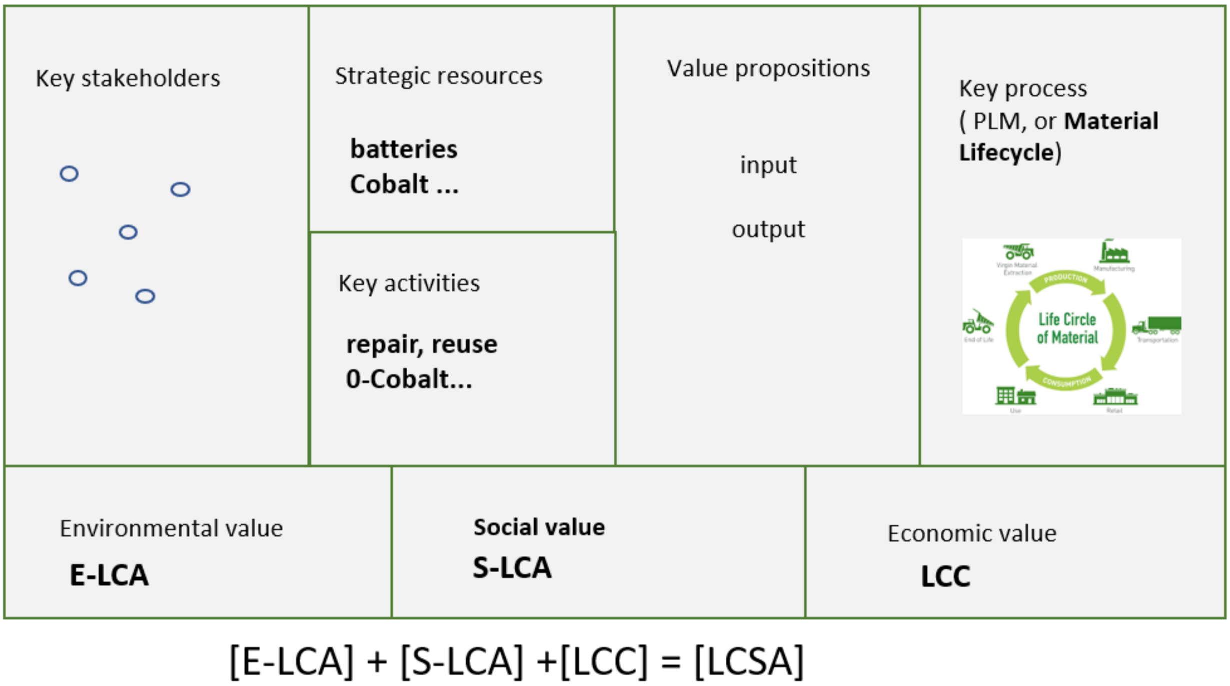


Fig.3. Adapted sustainable business model canvas [10] adapted from Osterwalder and Pigneur [11].

A. *Key Stakeholders*

Typically, stakeholders in a business are in three categories [12]: (a) internal or external; (b) primary or secondary; (c) direct or indirect.

In August 2019, the Business Roundtable introduced a new stakeholder model that redefined the purpose of corporations. According to this model, businesses have the explicit responsibility to serve multiple stakeholders, including shareholders, customers, employees, communities, the environment, and suppliers. The stakeholder model represents a growing strategic vision for companies. Environmental, Social and Governance (ESG) metrics can be utilized to evaluate a company's performance and its position concerning a wide range of topics relevant to a broader set of stakeholders. These metrics serve a similar purpose as financial metrics, which assess company performance for shareholders [13].

This paper focuses on the essential questions and guidelines for evaluating a company's preparedness in implementing ESG metrics and goals within executive incentive programs.

Fig. 5 presents Pay Governance's generalized viewpoint on the alignment between ESG initiatives and stakeholders. It is important to note that the matrix provided below is merely illustrative and does not encompass all ESG metrics and stakeholder impacts [13]. Fig. 6 shows the stakeholder influence matrix derived from a survey in 2021 and interviews with stakeholders from electronic companies, e.g., Siemens, Huawei, Nokia and Samsung.

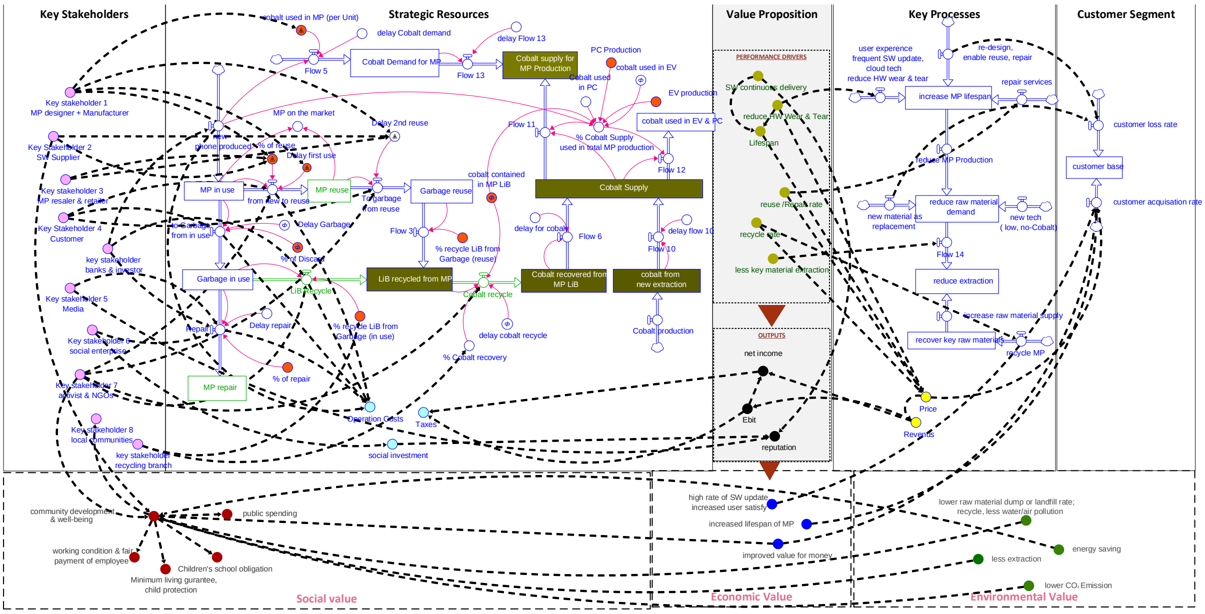


Fig.4. Adapted dynamic business modelling for sustainability applied to cobalt usage in a smartphone lifecycle.

Class	Category	Example Subcategories	Employees	Community	Suppliers	Customers	Shareholders
Environment	Carbon and Climate	• Energy and fuel efficiency • GHG emissions • Technology and opportunity (investments)		✔	✔		✔
	Natural Resources	• Water (use and pollution) • Land, forests, biodiversity (use and pollution) • Sustainable sourcing		✔	✔		✔
	Waste and Toxicity	• Hazardous and non-hazardous waste • Emissions and spills • Electronic waste • Packaging material	✔	✔	✔	✔	✔
	Management of Environmental Risk	• Disaster planning, response and resiliency • LEED design and certification	✔	✔	✔	✔	✔
Social	Human Rights	• Ethical sourcing • Supply chain standards	✔	✔	✔	✔	✔
	Labor, Health, and Safety	• Fair wages, benefits, training and development • Labor standards, job stability, and mobility • Employee engagement	✔	✔	✔		✔
	Diversity and Inclusion	• Equal opportunity and participation	✔	✔	✔		✔
	Product Safety, Quality, and Brand	• Customer satisfaction • Affordability and accessibility	✔	✔		✔	✔
	Community Engagement / Partnerships	• Volunteer hours • Workforce/community demographic parity • Alliances with key organizations, councils, and institutions • Corporate philanthropy	✔	✔			✔
Governance	Board Composition	• Minority representation • Gender equality	✔	✔		✔	✔
	Ethics and Compliance	• Anti-corruption • Cybersecurity and data privacy • Oversight and accountability • Management policies, systems, and disclosure (transparency) • Political contributions/lobbying	✔	✔	✔	✔	✔
	General Corporate Governance	• Executive compensation • Board leadership/structure • Share structure (multiple classes, board election)	✔				✔
	Risk Management and Mitigation	• Code of conduct • Sensitivity analysis and stress testing	✔	✔		✔	✔

Fig.5. ESG metrics and stakeholder impacts [13].

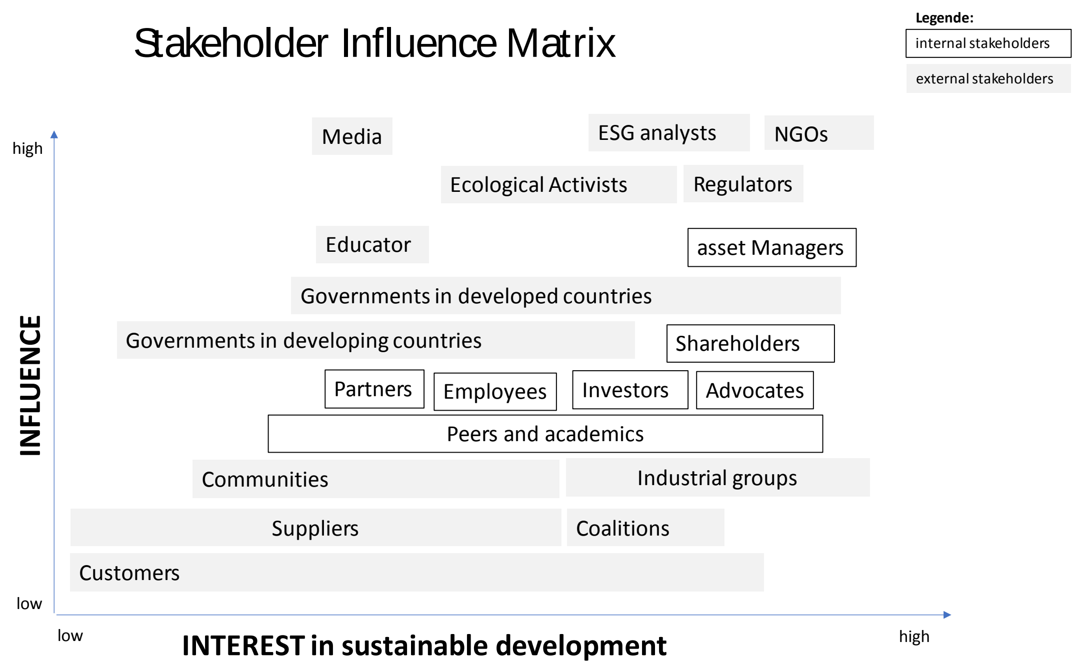


Fig.6. Key stakeholders and stakeholder-influence matrix [9].

B. Strategic Resources

A strategic resource is an asset that is valuable, rare, difficult to imitate and non-substitutable. Strategic resources refer to assets that provide a competitive edge to a business and are challenging for competitors to replicate. Three fundamental company resources that synergize to establish a competitive advantage are (a) financial strength, (b) enterprise knowledge, and (c) the workforce [14]. These strategic resources are crucial for creating and delivering a unique value proposition, accessing markets, nurturing customer relationships, and generating revenues [15]. SD differs from other simulation approaches (e.g., agent-based modelling) because it adopts a systemic perspective for mapping value generation processes and underlying Business Model (BM) variables, thereby integrating feedback loops, accumulation and depletion processes of strategic resources, time delays and nonlinear interplays among BM elements [1] [16].

Taking e-mobility in the EU as an example, Fig. 7 shows the Raw materials in e-mobility and supply bottlenecks. The colour code (**red** to **green**, and from left to right) stands from largest to smallest. The deployment of many technologies supporting the e-mobility sector will greatly impact the demand for materials in the future. In particular, the rare-earth elements (neodymium, dysprosium and praseodymium) and boron are likely to be in a large majority of motors in electric vehicles (EVs). Mobile energy storage will require critical raw materials e.g., **lithium**, **cobalt**, and natural graphite in Li-ion batteries (Li.B.) and platinum in Fuel cells. Structural parts and lightweight structures of vehicles will require materials such as magnesium, niobium, silicon metal and titanium.

As vehicles become increasingly more electronic, they will consume gallium, germanium, and indium in, for example, sensors, displays, circuitry, etc. Other alloying elements like chromium, tungsten and vanadium are in demand by almost all technologies [17].

C. Key Activities

The Key Activities Building Block outlines the critical actions that a company must undertake to ensure the success of its business model (BM) [18]. The specific Key Activities required may vary depending on the type of business model being employed.

For consultancy companies, like McKinsey, Key Activities of this type relate to coming up with new solutions to individual customer problems, in other words, problem-solving.

Business models that revolve around a platform as a key resource heavily rely on a platform or network-related key activities. For instance, in the case of eBay, their business model necessitates the continuous development and upkeep of their platform, specifically the eBay.com website. On the other hand, PC manufacturer Dell, their key activities centre around product design, manufacturing, and efficient delivery in significant quantities and/or with superior quality. In the business models of manufacturing firms, production-related activities such as manufacturing and supply chain management take precedence [15].

Mobile phone manufacturers and service providers, like Apple, Samsung, and Huawei combine the activities mentioned above. New designs (with low-cobalt or cobalt-free battery, replaceable components, repair-enabled design) and manufacturing are more production related; Re-use and online software updates to extend smartphone/mobile phone life span are problem-solving related.

D. Value Propositions

The "Value Proposition" refers to the combination of products and services that deliver value to a particular customer segment [19]. A company's value proposition is the reason why customers turn to that company over another. customer value creation can stem from various elements, and the following non-exhaustive list highlights some contributing factors: newness, performance, customization, delivery quality, product quality, productivity, design, price, convenience/usability, accessibility, reputation, cost reduction, and more [20].

The value proposition component describes environmental, social and economic forms of value (labelled as "profit, people and planet" in the framework), the value creation and delivery system depicts how internal resources, capabilities and activities are used in partnership with a wide set of stakeholders and the value capture system moves from selling products to more environmentally and socially sustainable ways of generating profits (e.g., selling services, paying per use, or paying for performance) [1].

The value proposition can also be divided by its flow direction into input and output values. The input of value can be raw material, manpower, energy consumption, next to design, production; the output of values can be the final product, net income, EBIT, reputation, water effluents, air emission, solid wastes etc.

E. Key Processes in Review of Battery Lifecycle

The key processes mentioned here are:

- Material production
- Battery manufacturing
- Recycling of battery and battery materials
- Cradle-to-grave lifecycle energy comparison of batteries. (incl. Emissions analysis. e.g., carbon dioxide emissions, criteria pollutants, and other emissions).
- Environmental/social/economic values
- The value proposition is the section that undergoes the main changes concerning its original formulation to combine the multiple perspectives of value offered by the organization, thus including not only short and long-term results but also viability and profitability with sustainability. Such a building block is divided into subsections addressing (a) value drivers, that is, those critical success factors affecting key processes thus providing a source for competitive advantages; (b) outputs, that is, short-term results achieved by the firm; (c) outcomes, that is, long-term results impacting on the broader context where the firm operates. With the intent to better frame the sustainable value dimensions and span the organizational boundaries of the firm, outcomes are further classified into (a) environmental value, (b) social value and (c) economic value [1].

As mentioned, earlier, the Life Cycle Sustainability Assessment (LCSA) can be expressed by the following conceptual formula as in (1) [21]:

$$[E\text{-}LCA] + [S\text{-}LCA] + [LCC] = [LCSA] \qquad (1)$$

where E-LCA denotes the conventional environmental life cycle assessment; S-LCA (Social Life Cycle Assessment) represents the assessment of positive and negative social impacts along the product lifecycle.

Environmental Values (E-LCA): cover values which belong to diverse categories, like carbon & climate, natural resources, waste & Toxicity, and management of Environmental risk. E.g., Energy saving, and CO2 emissions.

Social Values (S-LCA): covers human rights, labour (Null- Child Labour), health and safety, fair payment, good working condition, diversity and inclusion, community engagement and partnership.

Economic Values (LCC): Efficiency (net present Value and improved value for money) and quality as economic dimensions of perceived values.

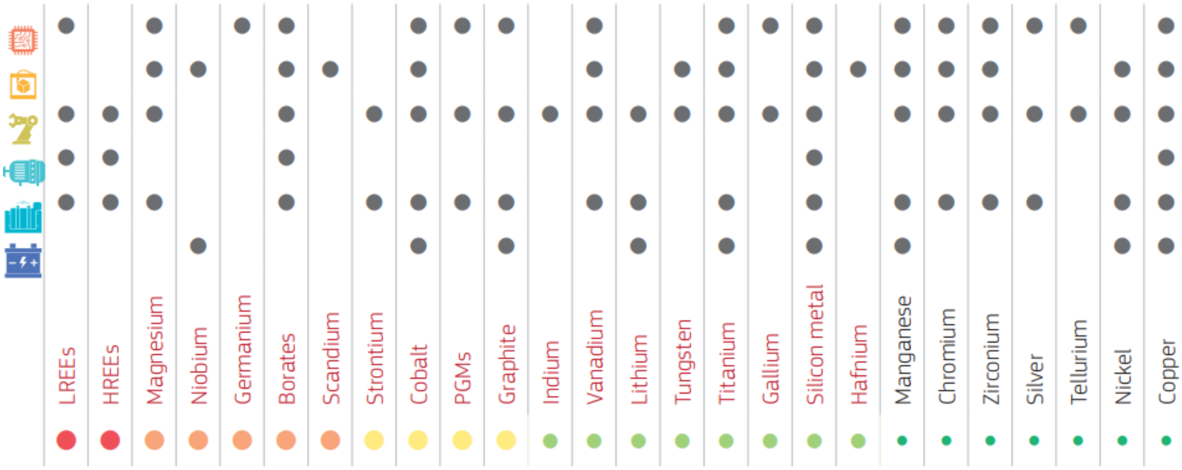


Fig.7. List of materials used in e-mobility sorted by their 2020 supply risk [17].

F. System Boundaries

LCSA pertains to the systematic evaluation of environmental, social, and economic impacts associated with products throughout their entire lifecycle. This assessment approach aims to integrate sustainability considerations into the decision-making process, ensuring a comprehensive understanding of a product's sustainability performance from its creation to its end-of-life stage [21] [22].

Although it involves several aspects including environmental and economic, our study focuses on the social impacts. The system boundaries in the battery industry are presented in Fig. 8. This research focuses on three categories: sustainability, environment and social. The environmental part is divided into two subcategories - upcycling and recycling. Upcycling focuses on the evaluation of smartphone function prolongation and recycling focuses on the reduction of the environmental impact of smartphone disposal by recycling its parts. The social category focuses on social issues created by resource extraction and the manufacturing process [23].

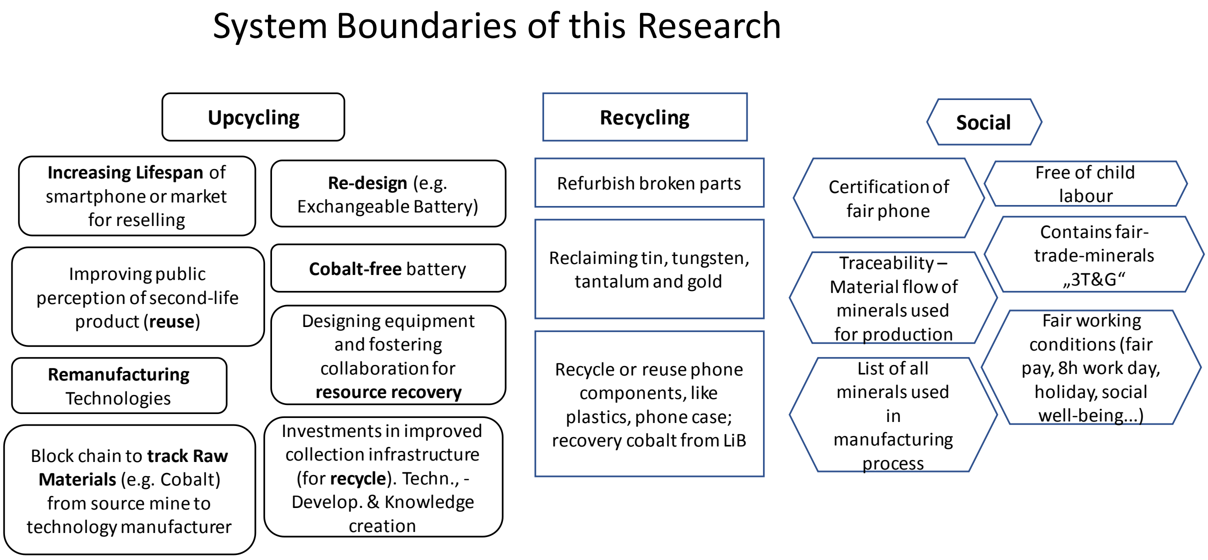


Fig 8.System boundaries of this research [9].

IV. A Case Study wit Smartphone

In this study, the smartphone was selected as the study subject due to its ubiquity and the global collaboration associated with various product types.

A huge part of the world 's population uses smartphones.

- 7.9 billion people by 2020
- 6 billion smartphones end of 2020
- An average of 1.5 billion new smartphones are produced per year
- 36 smartphones are produced per second, which exceeds the human birth rate

A typical smartphone lifecycle includes the following:

- Mine/Mine Traders#, Smelters/Refinery in the Democratic Republic of the Congo (DRC)#
- Design, development, marketing, and creation of software in the USA
- Mixed-signal chips (such as NFC): NXP from Netherlands; accelerometer from Bosch in Germany, Gyroscope from Italy/France
- Smelters/Refinery in China
- Batteries** & Flash memory from Korea
- Display/Camera and eCompass from Japan
- Touch ID Sensor and DRAM are mostly from Taiwan
- Plastic Construction in Singapore
- Assembly in China#
- Disposal/Dismantle/Recycle## done mostly in Africa and China

Fig.9 presents the globalization of a typical smartphone. Child labour is likely to exist in the smartphone's supply chain, e.g., in Resource extraction and process, or the End-of-Life phase. Recently, many have expressed concerns over smartphone issues such as adverse impacts on the environment from pollution in manufacturing and failure to recycle. The industry pays workers poorly, provides unhealthy working conditions and employs children [24].

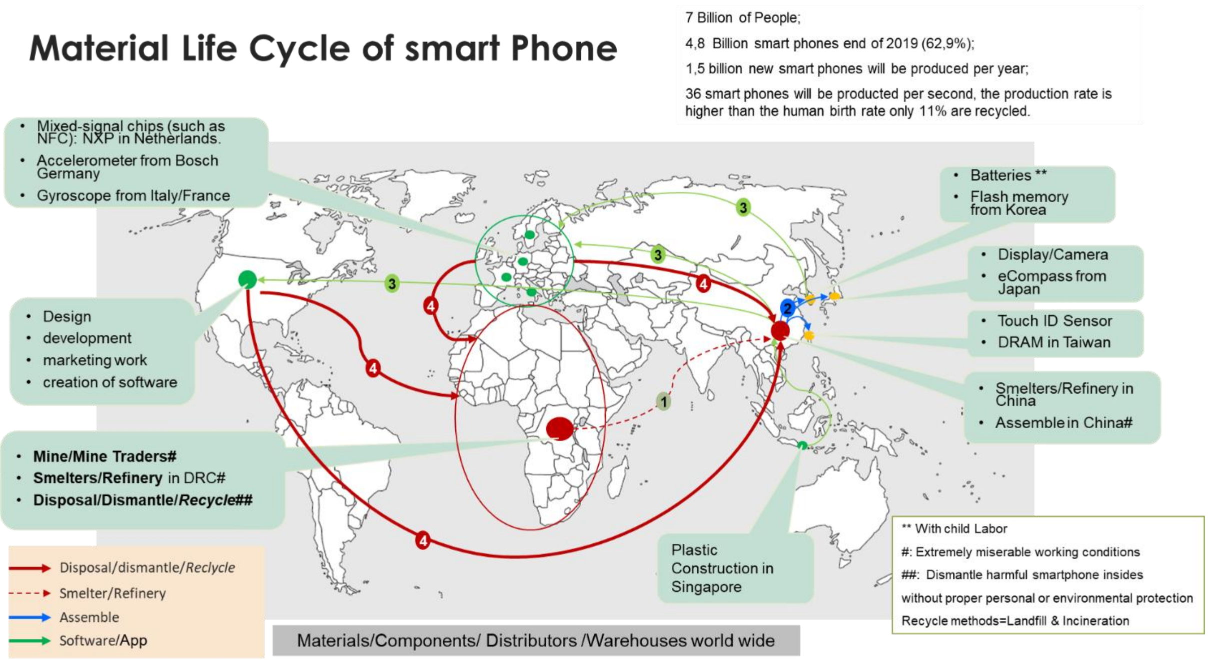


Fig.9.The material lifecycle of smartphones [9].

Fig. 10 shows that smartphone manufacturers use deadly chemicals and up to 46 precious materials, like tin, tantalum, tungsten, Gold (3TG) and cobalt.

In 2020, smartphones averaged 8 grams of cobalt vs. 28 grams in a laptop and 6803 grams in an electric vehicle. Statista, the global business data platform, reported 1.38 smartphones sold to end users worldwide in 2020 and projected 1.53 billion by 2021. In 2020 about 222.5 million laptops were shipped and 276.8 million were expected in 2021. The No. of electric vehicles reached 6.0 million at the end of 2020. The total amount of cobalt used in smartphones is about 11250 tons vs. 62967 tons in laptops and 40800 tons in electric vehicles (EVs).

Fig. 10. Application of tantalum, molybdenum and other metals In mobile phones [25].

TABLE I summarizes the total cobalt usage by the end of 2020 in different electric devices. The total cobalt usage in Smartphones counts almost 20% of the total cobalt usage by 2020, whereas the cobalt used in EVs counts for about 69% of total cobalt usage.

TABLE I. COBALT USAGE IN ELECTRONICS BY THE END OF 2020

Smartphone	Laptop	Electric Vehicle
7.5 grams of cobalt per unit	1 ounce (28.3 grams) of cobalt per unit	15 lbs (6.8 kg)of cobalt per unit
1.5 billion sold	222.5 million sold	6.0 million sold
11250 tonstotal cobalt used	6296.8 tons total cobalt used	40800 tons total cobalt used

Cobalt is a naturally occurring metal found in rocks, water, plants, and animals. Compared to many other metals, cobalt is relatively less toxic. In small amounts, it has beneficial effects on human health and is a component of vitamin B12. However, high levels of cobalt can be dangerous. The health risks associated with cobalt exposure depend on the duration and quantity of exposure. The Centres for Disease Control and Prevention (CDC) in the United States have issued warnings about the potential health effects of chronic cobalt exposure, which can lead to a condition known as "hard metal disease." Even skin contact with cobalt salts or hard metals can result in skin rashes. The CDC has set a safe workweek limit of 0.1 milligrams per cubic meter for cobalt exposure [26].

Cobalt is utilized in various applications, including alloys, semiconductors, fertilizer, and as a drying agent for varnish and enamel coating on steel. In the form of cobalt sulphate, it plays a crucial role as a cathode stabilizer in lithium batteries (Li.B.). The demand for lithium-ion batteries is rapidly increasing due to the growing popularity of electric cars, laptops, and mobile phones. Consequently, cobalt, which was once considered a low-value chemical, has become a subject of competition among the world's largest economies [26].

According to a study by Kosiorek and Wyszkowski [26], global cobalt production increased more than sevenfold between 2008 and 2015, resulting in a noticeable impact on the market. "The appearance of cobalt levels exceeding environmental threshold levels has led to disturbances in the proper functioning of living organisms," the paper concluded.

Amnesty International says human rights abuses, including the use of child labour in the extraction of minerals to make the batteries that power electric vehicles, are undermining ethical claims about the cars.

The environmental impact associated with cobalt extends throughout the entire lifecycle of the product, starting from refineries and battery plants to consumer goods manufacturers, electronic recycling facilities, and waste disposal sites. However, one of the most significantly affected groups is the workers in poorly regulated mines [26] [27]. Child labour as allegedly reached alarming levels in the Congo. Not only is it the largest cobalt mining country globally, but this country is also by far the largest producer of cobalt intermediates. They produced 87.7kt cobalt contained in intermediates in 2020, accounting for 68% of the global supply [1][9].

V. Conceptual Modelling and Developing Causal Loop Diagram

Causal Loop Diagrams (CLDs) have been widely accepted and employed in conventional system dynamics practice for various purposes related to simulation modelling. In practice, CLD is primarily utilized as a preliminary step before conducting simulation analysis. The purpose is to visually represent the fundamental causal mechanisms hypothesized to drive the reference mode of behaviour over time. CLD serves as a means to articulate a dynamic hypothesis of the system, highlighting how the endogenous consequences emerge from the feedback structure [16]. CLD not only establish a connection between the structure of a system and the decisions that drive its behaviour but also has expanded its applications beyond the model building. They are now utilized for purposes such as detailed system descriptions and standalone policy analyses [28] [29]. In the upcoming section, a more comprehensive introduction will be provided, covering the terminologies, concepts, and tools employed in system dynamics.

A. Causal Loop Diagrams

System Dynamics employs both qualitative and quantitative tools to comprehend the structure and behaviour of complex systems. One such tool is the Causal Loop Diagram.

CLD diagram is made up of nodes and edges. Nodes are variables and edges are links that represent a connection or relationship between two variables. A positive link indicates a positive relationship, while a negative link indicates a negative relationship. A positive causal link indicates that the two nodes change in the same direction, i.e., if the node where the link begins decreases, the other node decreases as well. Similarly, if the node from which the link originates grows, so does the other node. A negative causal link indicates that two nodes or variables change in opposite directions [30].

A CLD is a qualitative representation of a hypothesis. It visualizes the causal links that connect various elements within a system. These causal links form the basic operating unit of the system, known as the Feedback Loop. By representing the feedback loops, causal loop diagrams provide a visual depiction of how the elements of a system interact and influence each other [31].

There are two types of causal loops in systems thinking: reinforcing and balancing. Change in one direction is compounded by more change in a reinforcing loop. Balancing loops counteract change in one direction with change in the opposite direction. Balancing processes attempt to bring things to a desired state and keep them there, like how a thermostat regulates a house's temperature [32].

For example, as seen in Fig. 11, when a human is hungry, its body sends a signal to the brain that it is time to eat, which appeases hunger [32].

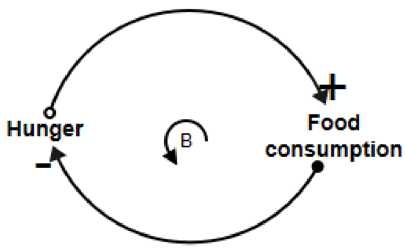


Fig.11. Representation of a balancing loop**[32]**.

In contrast, a reinforcing loop occurs when an action influences more of the same action, resulting in growth or decline [32]. For example, as seen in Fig. 12, money in a savings account generates interest, which increases the balance in the savings account and earns more interest [32].

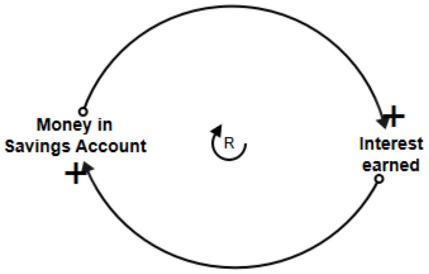


Fig.12. Representation of a reinforcing loop**[32]**.

Lannon introduced one quick way to tell if a loop is reinforcing or balancing, just by counting the number of "–". The loop is reinforcing if there are an even number of "–" (or none). It is a balancing loop if there are an odd number of "–" [32].

In summary, CLD visually represents and analyses the dynamics and interactions between multiple variables within a system, allowing for the qualitative or quantitative understanding of these relationships [33].

B. Problem Identification

Several challenges threaten sustainable development goals; especially when the challenge of taking its social aspect into account to analyse the fast-expanding global industries like commercial aircraft, automobiles, mainframe computers and consumer electronic equipment [34]. Globalization widened and extended the business system boundary, often at the expense of the environment, and social welfare in under-developed countries. This problem is especially serious in the electronics industry, the battery industry is particularly problematic because the electronics industry emerged in the 20th century and is today one of the largest global industries.

The known issues are child labour, unfair payment, poor working conditions etc.

Down to the smartphone level, the Issues raised during development are for example, (a) too many spare phones, (b) battery life has potent for enhancement, (c) heavy reliance on cobalt for Lithium-ion Batteries, (d) Glass screens and glass backs are easily broken, etc. Sustainability issues in the smartphone lifecycle happened mainly in the upstream supply chain, i.e., poor working conditions, low living wages, long working hours, harmful practices of mining, extraction and processing, energy & resources intensive manufacturing processes, etc.

Further down to the battery level, the acute problems are:

- Battery life is getting shorter.
- Non-replaceable or non-repairable batteries Design
- Battery failure
- Heavily reliance on lithium-ion batteries
- Recycling lithium-ion batteries is expensive and challenging.
- Low-cobalt or cobalt-free batteries for smartphone is a breakthrough but have not yet matured.

1 Cobalt issues are paramount, e.g., it is unclear what are the best ways to reduce cobalt extraction while satisfying the increasing demand for cobalt in Lithium-ion batteries. Possibilities include:

- Reduce cobalt extraction from mines, especially from ASM mines.
- Increase cobalt recovery from scrap or Li.B.
- Extend the cobalt usage cycle by extending the smartphone lifespan.
    - Increase the 25% smartphone recycle rate or extend the 2.5-year smartphone lifespan to reduce the demand for new cobalt, especially cobalt extracted from mines.
    - Extend the lifespan by reuse, repair, refurbishment, remanufacturing, and recycling.
- Apply low-cobalt or cobalt-free battery technology.

Forced **child labour** is chosen to represent the social sector because modelling social sustainability in detail would increase the size of the model, take more time, lose the essence of the issue and decrease the understandability of the model.

Cobalt is taken as one of the key raw materials because it comes from mines in areas with severe social problems.

C. Purpose of the Model

The minimal goal is to reduce demand for cobalt, therefore reduce the child labour used in cobalt extraction from Artisanal and Small-scale cobalt mines (ASM). Child labour in mining is most found in artisanal and small-scale mines. Without concerted action, the growing ASM sector will result in an increasing number of children being involved in mining activities.

ASM mines refer to the mining of cobalt conducted on a smaller and more localized scale. DRC accounts for over 70% of global cobalt production, with approximately 15-30% originating from artisanal and small-scale mines. In these mines, independent miners utilize their resources to extract the mineral [35].

ASM encompasses a wide range of forms, including official cooperative associations as well as illegal operations by small groups of miners on mining concessions. The sector is predominantly informal and lacks mechanization, with individuals often relying on manual tools and basic extraction methods. Consequently, ASM poses significant safety and human rights risks. Of particular concern is the involvement of children in the sector [36].

Fig. 13 shows a simplified conceptual model that simulates cobalt extraction and child labour usage in a smartphone. The parameters will be defined in the coming section. The colour coding scheme used in this context assigns a **blue** colour to external variables, **red** to internal main parameters, and **black** to internal secondary parameters.

D. Paremeter Identification

In this section, the parameters used in Fig. 14 will be defined:

- Parameter 1: demand for cobalt
- Parameter 2: child labour (in ASM mines)
- Parameter 3: cobalt extraction from ASM mines
- Parameter 4: cobalt extraction from industrial mines
- Parameter 5: total cobalt extraction from mines
- Parameter 6: cobalt supply
- Parameter 7: cobalt recovery (from Li.B. or scrap)
- Parameter 8: invest in cobalt recovery tech.
- Parameter 9: cobalt-free/ low cobalt technology
- Parameter 10: cobalt price
- Parameter 11: smartphone price
- Parameter 12: reuse of smartphone
- Parameter 13: repair of smartphone
- Parameter 14: formalization of ASM mines
- Parameter 15: women in the working market
- Parameter 16: miners' income
- Parameter 17: children in school
- Parameter 18: regular software updates & security patches

Acknowledgment *(Heading 5)*

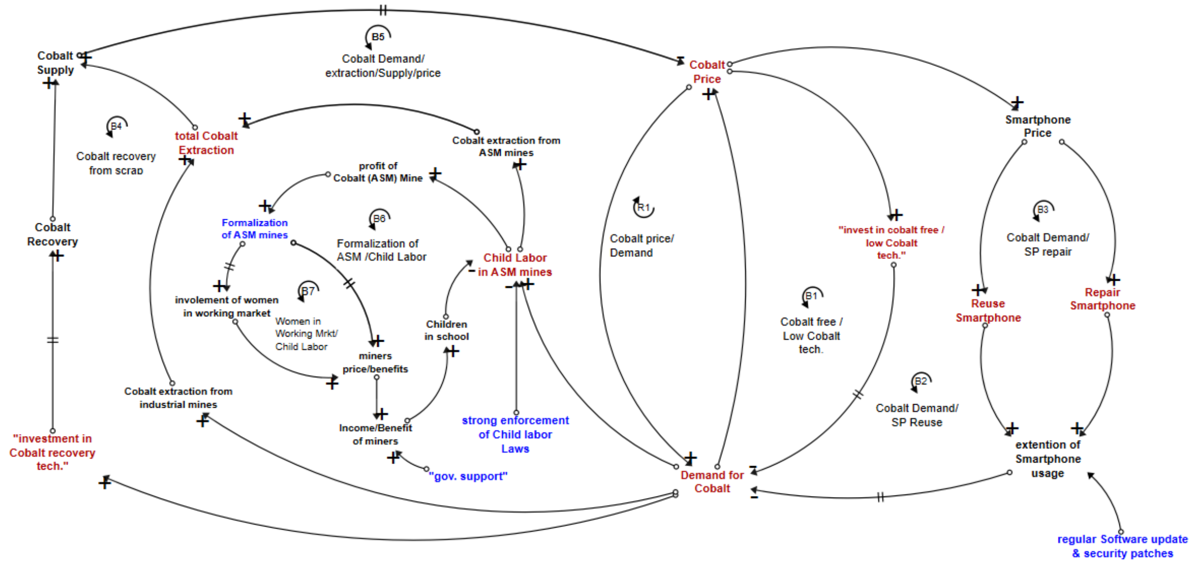


Fig.13. Causal loop diagram of reducing demand for cobalt, reducing child labour in the smartphone case study.

Legend of this CLD:

R1 (Reinforcing Loop 1): "Demand for cobalt - cobalt price" Reinforcing Loop

The demand for cobalt increases, and the higher the cobalt price goes. As a result, the intensity of demand is increased.

B1 (Balancing Loop 1): "Demand for cobalt - cobalt price -cobalt free/ low cobalt tech." Balancing Loop

The demand for cobalt increases, and the higher the cobalt price goes. the greater the sense of looking for cobalt-free or low-cobalt technology. As a result, the intensity of demand for cobalt is reduced.

B2 (Balancing Loop 2): demand for cobalt – cobalt price – smartphone price -smartphone reuse – smartphone lifespan extension Balancing Loop

The demand for cobalt increases, and the higher the cobalt price goes, the smartphone price increases too, and the greater the sense of reusing /refurbishing a smartphone. As a result, the smartphone stays longer in usage, before it will be discarded. the intensity of demand for cobalt is reduced.

B3 (Balancing Loop 3): "demand for cobalt – cobalt price – smartphone price - smartphone repair – Smartphone lifespan extension" Balancing Loop

The demand for cobalt increases, and the higher the cobalt price goes, the smartphone price increases too. the greater the sense of repairing a smartphone. As a result, the smartphone stays longer in usage, before it will be discarded. the intensity of demand for cobalt is reduced.

B4 (Balancing Loop 4): "demand for cobalt -investment for cobalt recovery -cobalt recovery – cobalt supply – cobalt price" Balancing Loop

The more demand for cobalt increases, the higher sense to put more investment into the cobalt recovery branch, and the more cobalt can be gained from scrap, which increases cobalt supply without necessarily increasing cobalt extraction from mines. As a result, cobalt price falls, and demand for cobalt falls too.

B5 (Balancing Loop 5): "Demand for cobalt -child labour in ASM mines -cobalt extraction from ASM Mine – total cobalt extraction – cobalt supply – cobalt price" Balancing Loop

The higher demand for cobalt, the more child labour is needed in ASM mines to ensure more cobalt can be extracted from mines, to increase the cobalt supply. When supply is more than enough, then the cobalt price may fall. As a result, demand for cobalt will be less intense.

B6 (Balancing Loop 6): "formalization of ASM mines – miner price/benefits -income of miners -children in school – child labour in ASM mines" Balancing Loop

Formalization is a crucial and intricate process that is essential for improving the lives of miners and addressing critical issues within supply chains. In the context of cobalt mining, formal miners reap numerous benefits by engaging in programs aimed at formalization. These benefits include access to markets and improved prices for their products. Through formalization, miners receive the necessary support to work responsibly and enjoy a safer working environment. Furthermore, evidence suggests that formalized miners can obtain better prices for their cobalt due to the formalization process [37].

When miners have enough income, they can afford the school expense of their kids, therefore more children can return to school, instead of going to AMS mines to earn food for the family.

B7 (Balancing Loop 7): "formalization of ASM mines – involvement of women in the working market - miner price/benefits -income of miners -children in school – child labour in ASM mines" Balancing Loop

With formalization, miners have more benefits, women will be more involved in the working market, therefore can help increase family income. The more income the family has, it will be easier for them to afford the school expense of their kids, therefore more children can return to school.

"**//"** on the arrows represents delay, a delay function is frequently needed in system dynamics for modelling postponed effects.

The CLD is continuously examined and analysed visually to identify the crucial variables and the assortment of balancing and reinforcing loops it encompasses. This process also involves simplifying the conceptual diagram to ensure that the resulting insights can serve as a foundation for policy development and implementation [38]. By adhering to the definition of feedback loops, researchers can gain an understanding of specific mechanisms within the system they are studying [39]. More parameters can be added in the scenario where the demand for cobalt experiences a significant rise, driven by the increasing sales of electric vehicles.

- Parameter 18: Reuse cobalt battery in portable devices
- Parameter 19: Production of e-Vehicles (EV)
- Parameter 20: EV demand for cobalt
- Parameter 21: Production of Smartphone
- Parameter 22: Smartphone demand for cobalt

2

Then the causal loop diagram of the whole situation becomes more complex, and at least one more loop can be identified. See the yellow high-lighted loop in Fig. 14.

B8 (Balancing Loop 8): "Production of EV – Demand for cobalt – cobalt Price – cobalt /Battery reused in Portable devices – Demand for cobalt" Balancing Loop

The dramatic increase of EVs increases demand for cobalt-based batteries, therefore, demand for cobalt increases, which drives cobalt prices to go up. Under the high price pressure, it makes more sense to reuse EV cobalt Batteries, for example, in any small portable devices or energy storage. In the long term, it slows down the demand increase for cobalt.

E. Stock and Flow Diagrams

The other common notation for system dynamics is Stock-and-Flow diagrams (SFDs).

According to Lin et al. [39], a stock and flow diagram consists of four main variables: stock, flow, auxiliary, and delay. These variables play essential roles in representing the dynamics and relationships within the system being modelled.

In the context of system dynamics modelling, the following concepts are described by Lin et al. [39]:

- Stock variables: These variables represent the "memory" of the system and carry over values from one time step to another. They define the system's state and influence other components within the system. An example is the volume of water in a container, where the previous volume affects the current state unless there are changes such as adding or draining water.
- Flow variables: These variables represent the changing aspects of the system and do not carry over values. They reflect the rate of change of a particular variable and can be categorized as inflow or outflow variables. For instance, the inflow variable represents the rate at which water enters the container, while the outflow variable represents the rate at which water leaves the container.
- Auxiliary variables: These variables influence the flows within the system but do not alter the overall mathematical structure. They contribute to the transparency of the model by providing additional information or context.
- Delay variables: These variables introduce a time lag between a causal action and its effect. They account for delays in policy interventions or changes in human behaviour patterns.

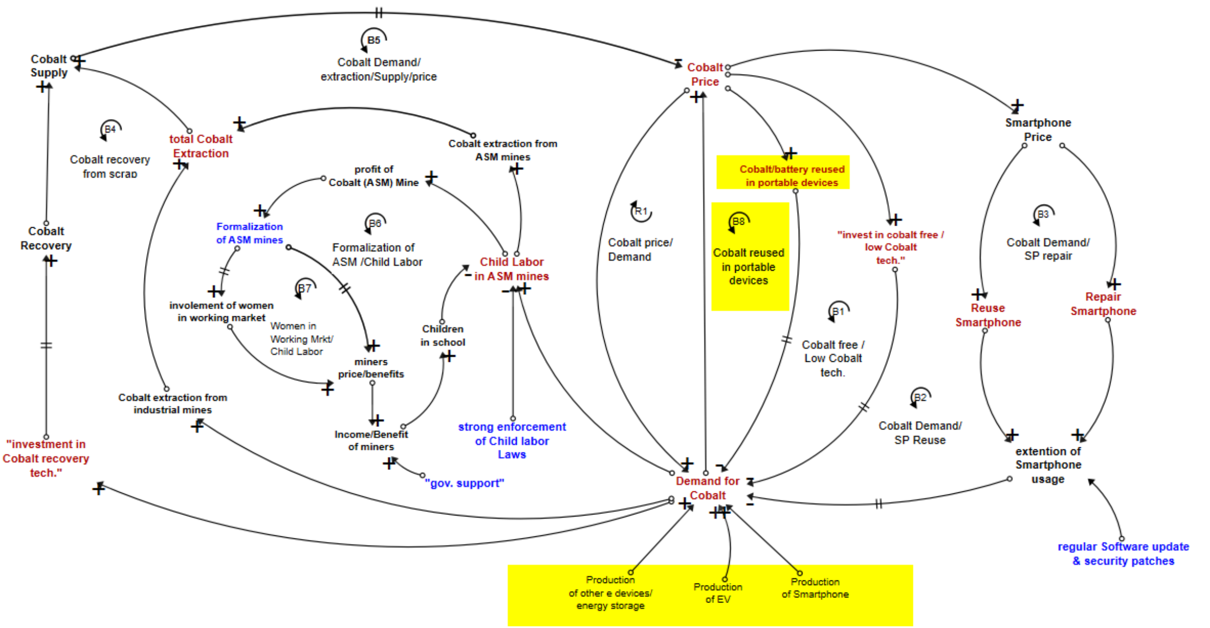


Fig.14. Causal loop diagram of the cobalt extraction and cobalt demand including e-vehicles & smartphones.

To demonstrate the formulation of a stock and flow equation, the stock variable 'Co. Supply' will be taken as an example depicted in Fig. 15.

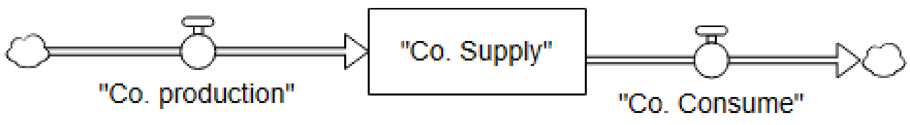


Fig.15. Stock-flow equation.

For the cobalt supply variable S, the primary components are the inflow (cobalt production IS) and the outflow (cobalt consume OS). Therefore, the equation representing this relationship can be written as in (2):

$$dS(t) / dt = IS(t) - OS(t) \qquad (2)$$

The inflow, admissions IS, in the model is equal to the cobalt production CP (auxiliary variable), see (3). This assumes that all cobalt production directly contributes to the supply. In real-life applications, cobalt production encompasses both new extractions from mines and recovery from scrap. To account for this, a delay variable and/or constraint could be included to capture the impact on cobalt supply. Thus,

$$IS(t) = CP(t) \qquad (3)$$

The outflow, cobalt consume OS, is determined by expressing it as a function of cobalt demand, assuming a fraction λ is consumed by smartphones. As previously stated, this value is subtracted in (4) as it represents an outflow:

$$OS(t) = l^* S(t) \qquad (4)$$

Substituting IS and CP, the differential equation for the stock variable S can be rewritten as in (5):

$$dS(t) / dt = CP(t) — I^* S(t) \qquad (5)$$

F. *Constructing System Dynamics Equations*

Based on the CLD/stock & flow diagram developed in Fig. 13, the conceptual model can be translated into mathematical equations. Each causal link in the diagram can be associated with a mathematical equation. Once all the equations are assigned, the system can be solved numerically as a set of ordinary differential equations using established methods for solving such equations [39].
System dynamics models can be constructed to formalize logic even with limited data. However, the model's effectiveness is significantly improved if the parameters can be determined through maximum likelihood estimation and if confidence intervals can be obtained using likelihood methods or bootstrapping techniques [40].

VI. Modelling with Simulation Software

A. *When to Use System Dynamics Simulation Model*

When a change has created a challenge, simulation is often used to:

- Increase the understanding of problems
- Improve existing systems
- Improve behaviours
- Reduce complexity
- Avoid black-box decision-making

The simulation software used in this research to implement the system dynamics model described above is STELLA® Architect (Version 2.1.x)[9].

B. *Preparing for System Dynamics Simulation*

- Problem definition: formulating a problem from a dynamic perspective
- Key variables: recognizing central factors and key variables
- Behaviour over time: recognizing and estimating the behaviour of key variables over time
- Feedback diagrams: identifying cause and effect, drawing feedback diagrams

C. *Model Building*

very undesirable to start, as many people in the field do, with causal loop diagrams. His modelling approach is to start with the system levels, showing the condition of the system. Levels can be defined as follows:

- How high is the smartphone reuse rate?
- How much capital investment can be motivated?
- Where are you in the use of the remaining natural resources (avoid cobalt extraction from mine, increase cobalt recovery from Batteries)?
- To what extent can the child labour issue be tackled?

Fig. 16 shows one example of model simulation with STELLA®for cobalt usage in the smartphone lifecycle.

D. *Model Calibration*

The model was calibrated step by step, parameter by parameter using real data.

- The typical time for long-term projects is 10 ~20 years.
- The measurements are those parameters for the model defined above.

Fig. 17 ~ Fig. 19 show the calibration result of the model. For example, Fig. 17 illustrates graphically the Model calibration concerning mobile phone reuse/repair & disposal. By calibrating Parameter 1 (Reuse), Parameter 2 (Delay of Reuse.) and Parameter 3 (Discard), increasing the rate of Reuse/Repair for mobile phones, extending the lifespan of mobile phones (increasing the delay of reuse), reducing the rate of discard (see the line for "MP in use") will reduce first then stay steady. More mobile phones are reused phones (see the line for "MP Reuse"). The total number of phones on the market stays steady too, assuming the population is unchanged. The more phones are reused, the part of garbage caused by reused phone increase too.

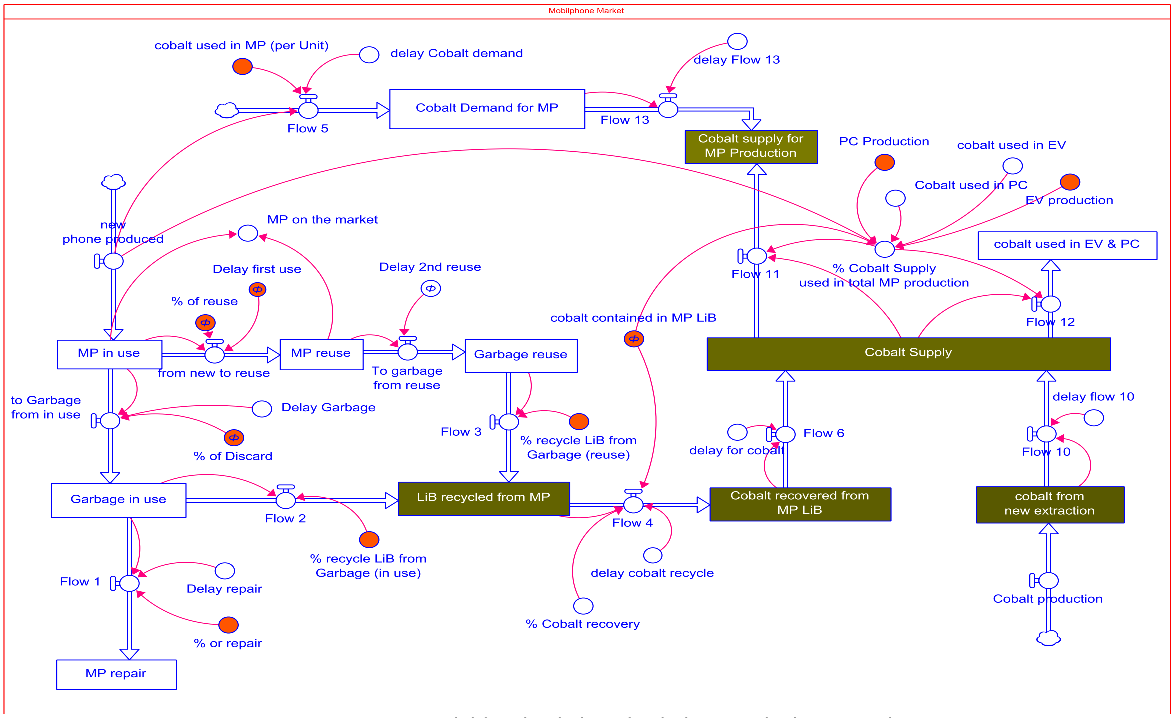


Fig.16. STELLA® model for simulation of cobalt usage in the smartphone.

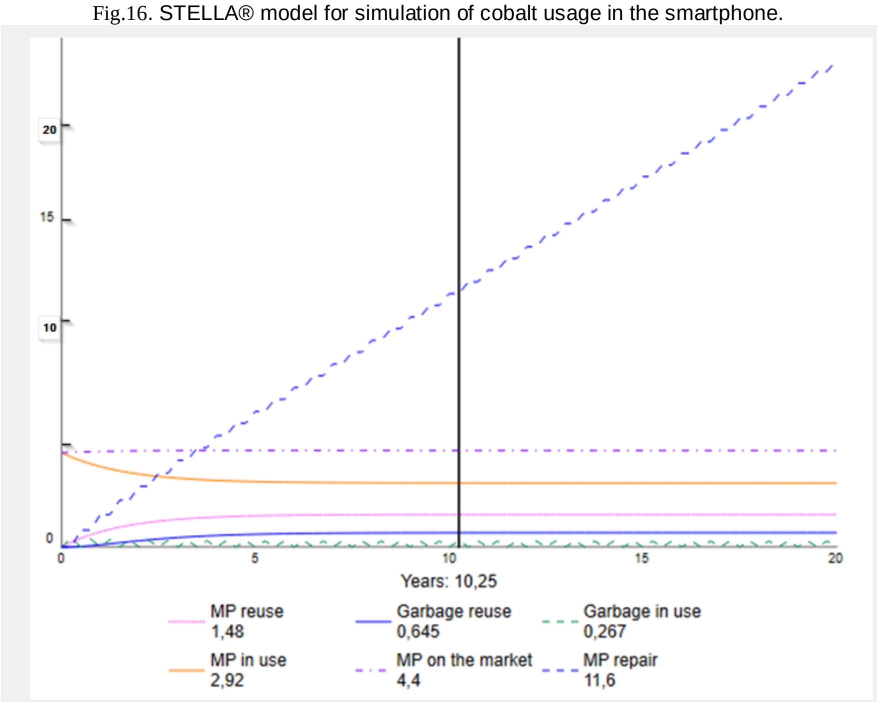


Fig.17. Model calibration for mobile phone reuse, repair, and discard.

Fig. 18 illustrates the model calibration concerning cobalt supply and demand. The X (horizontal) axis is the time axis, and the Y (vertical) axis is the unit axis, with measurement units in Tons. By calibrating Parameter 4 (Recovery Li.B. from discarded phone) & Parameter 5 (Recovery cobalt from Li.B.), increasing the rate of recovery of lithium batteries from mobile phones and the rate of cobalt recovery from lithium batteries, the cobalt supply for mobile phone production increases too. If the demand for cobalt keeps steady, then less cobalt would be extracted from mines. (See the vertical black line to year 8 in Fig. 18).

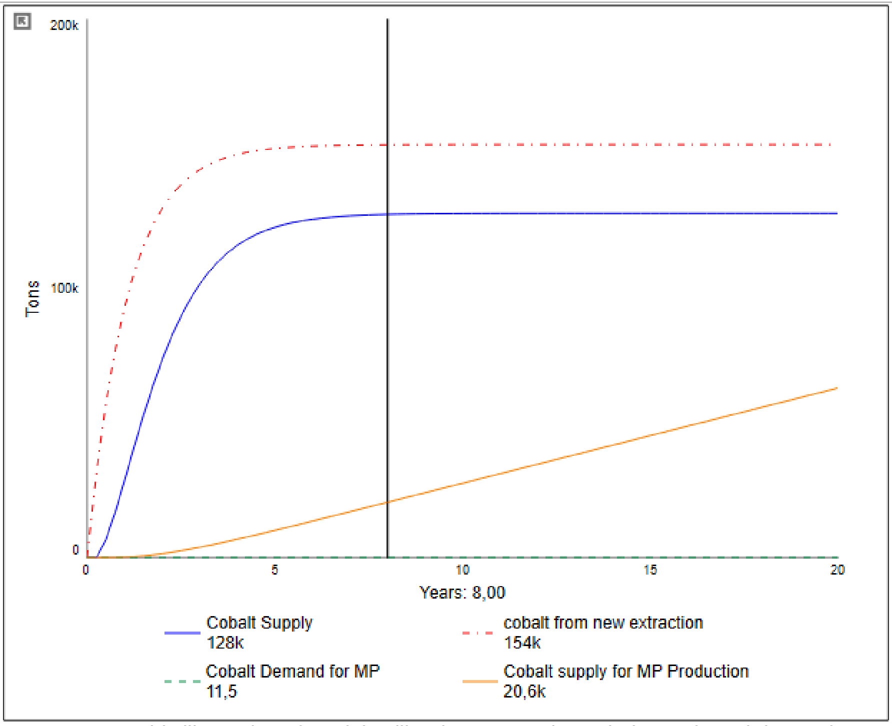


Fig.18. Graphic illustration of model calibration concerning cobalt supply and demand.

Fig. 19 shows the same change trend and synchronous change of lithium batteries recycled from mobile phones; cobalt recovered from mobile phone Li.B.

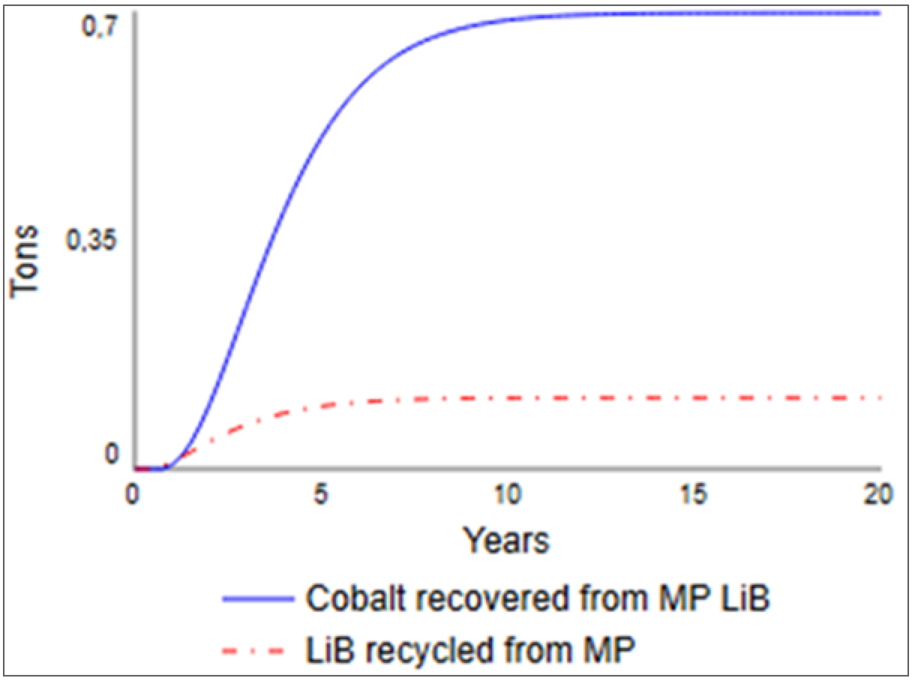


Fig.19. Timing of model calibration of Li.B. recycling and cobalt recycling for a mobile phone (MP).

E. Visualization and Simulation of Model

By leveraging the capabilities of STELLA®, users can effectively explore assumptions, simulate model behaviour, and analyse the results, ultimately enhancing their understanding and decision-making in complex systems [41].

Fig. 20 – Fig. 23 show the relationships and interactions between variables. Here "garbage reuse" is taken as output, and the relevant variables are "% of reuse rate", "delay of 1st. reuse", "delay of 2nd. reuse", "the rate of discard", "the amount of cobalt usage in each mobile phone unit".

TABLE IIlists the value set for each variable in each run. TABLE IIIis the simulation result of "Garbage Reuse" for each run over a period of 20 years.

TABLE II. VALUE SETTING FOR EACH VARIABLE

run \ variable	% of use	Delay 1st. use	Delay 2nd. use	% of discard	Cobalt contained in SP Li.B.
1. Run	0	2	0.5	100	10
2. Run	25	2.5	0.5	75	7.6
3. Run	50	5	2	50	5
4. Run	75	5	2	25	3
5. Run	90	10	5	10	0

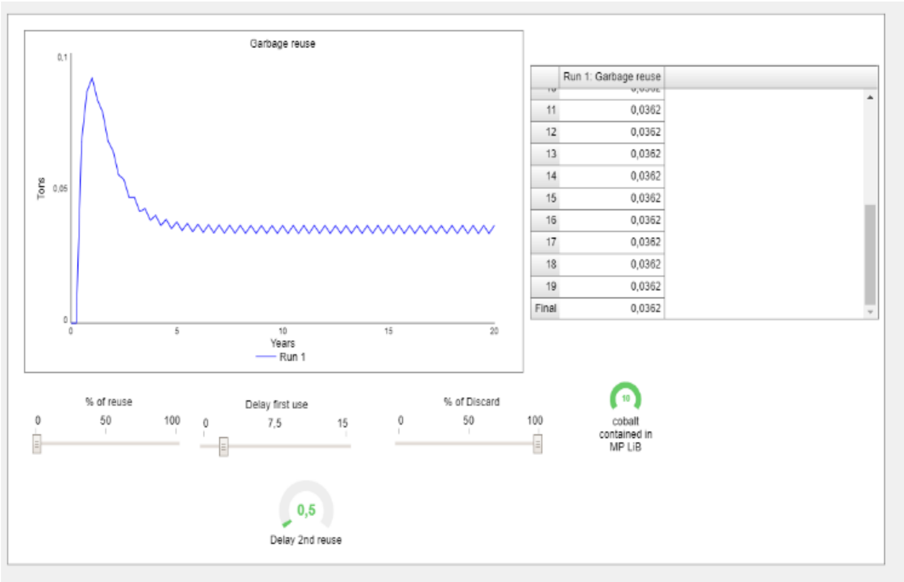


Fig.20. Simulation result after 1 run.

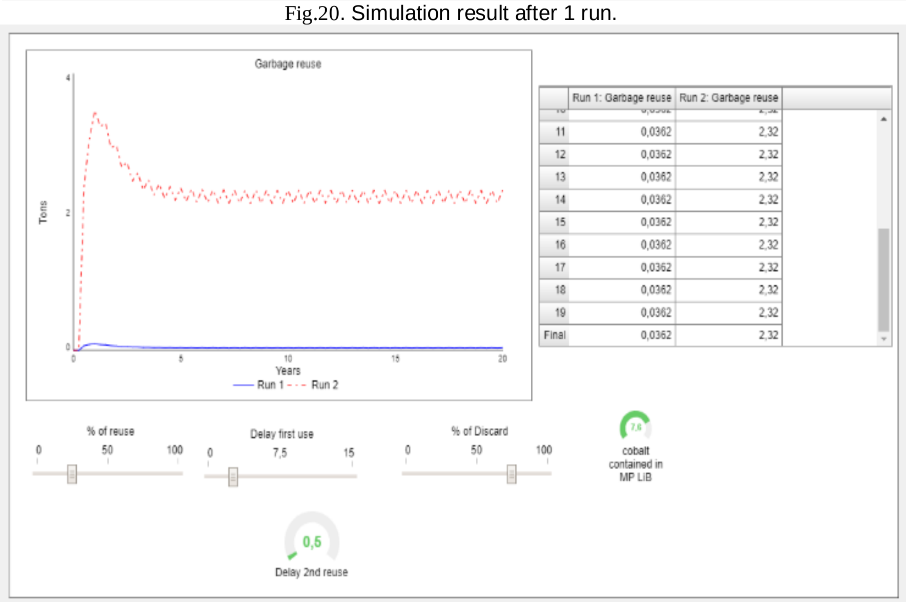


Fig.21. Simulation result after 2 runs.

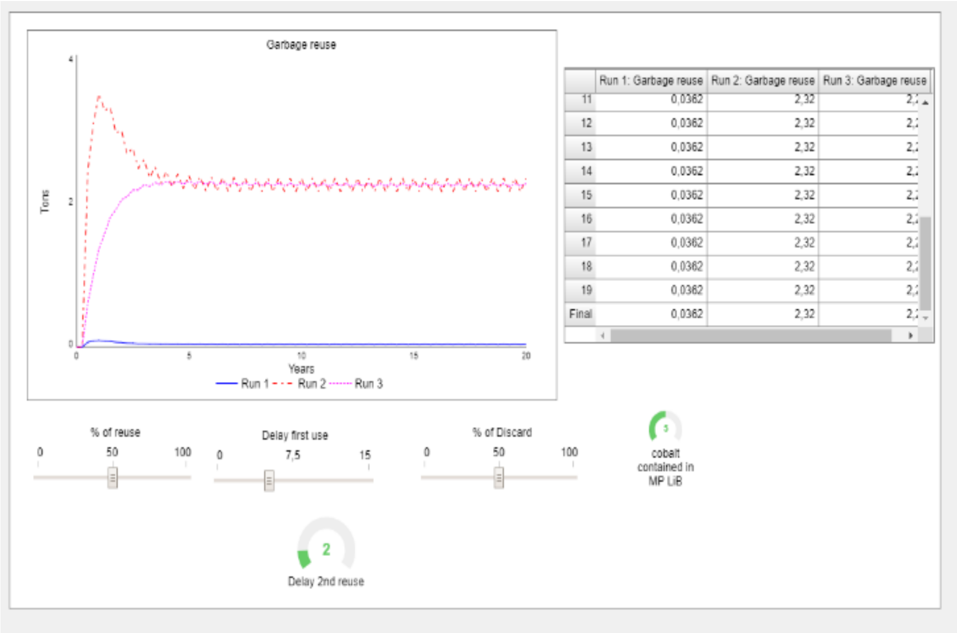


Fig.22. Simulation result after 3 runs.

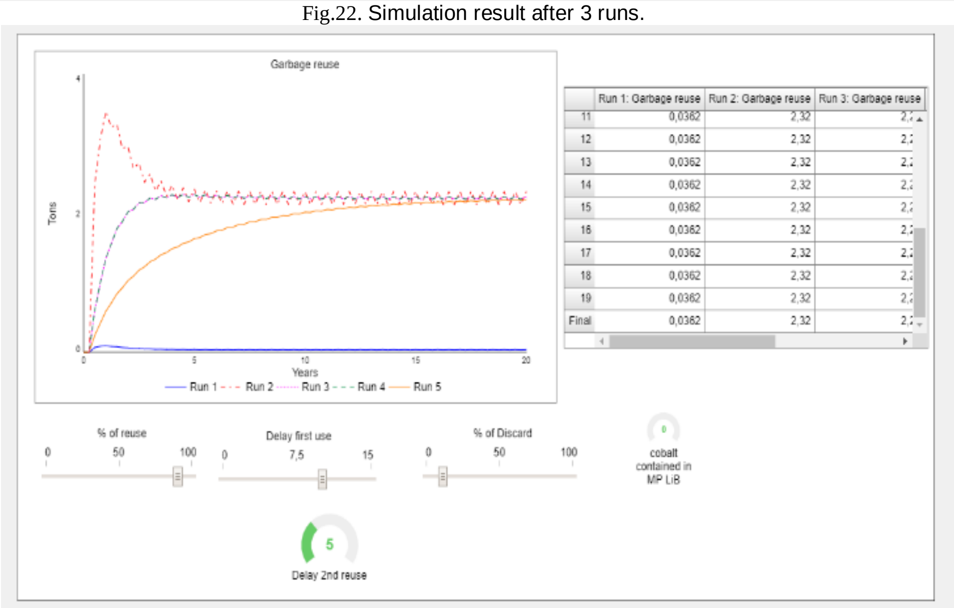


Fig. 23. Simulation result after 5 runs.

TABLE III. SIMULATED "GARBAGE REUSE" UNDER DIFFERENT CONDITIONS

Run / Year	Run 1	Run 2	Run 3	Run 4	Run 5
0	0	0	0	0	0
1	0.091	3.47	1.35	1.35	0.587
2	0.0637	2.97	2.02	2.02	1.03
3	0.0466	2.57	2.22	2.22	1.3
4	0.04	2.41	2.27	2.27	1.49
5	0.0376	2.35	2.27	2.27	1.64
6	0.0367	2.33	2.26	2.26	1.75
7	0.0364	2.32	2.26	2.26	1.84
8	0.0363	2.32	2.25	2.25	1.91
9	0.0362	2.32	2.25	2.25	1.97

10	0.0362	2.32	2.24	2.24	2.02
11	0.0362	2.32	2.24	2.24	2.06
12	0.0362	2.32	2.24	2.24	2.09
13	0.0362	2,32	2.24	2.24	2.12
14	0.0362	2.32	2.24	2.24	2.14
15	0.0362	2,32	2.24	2.24	2.15
16	0.0362	2.32	2.24	2.24	2.17
17	0.0362	2.32	2.24	2,24	2.18
18	0.0362	2.32	2.24	2.24	2.19
19	0.0362	2.32	2.24	2.24	2.2
Final	0.0362	2.32	2.24	2.24	2.2

Fig. 24 shows an extension of the model in Fig. 16 that covers financial aspects. Take repair as an example. Assume the repair cost per year per unit of a phone is about 30 Euro annually and a new phone cost about 200 Euro per year for a 2-year lifespan.

Fig. 25 and Fig. 26 show the simulation results of the total costs over time. To this time point, this simulation is simplified by assuming the repair also happens in the first two years of usage. Repairing a phone is worthwhile after about 3 years of usage if the average repair cost is about 30€.

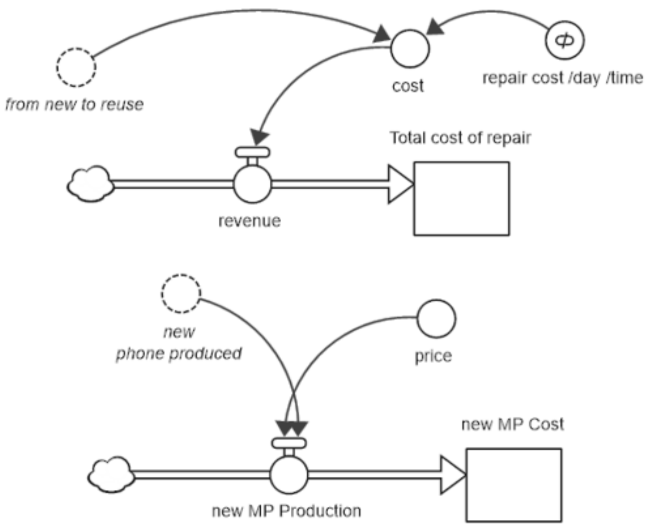


Fig.24. Financial sector of the model.

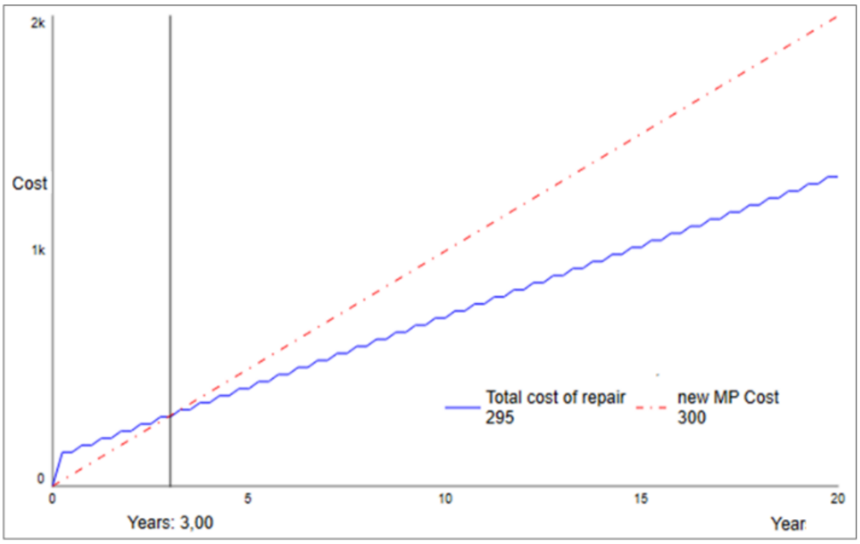


Fig.25. Comparison of new mobile phone cost and repair cost by reusing phone over time (Repair cost =30€ /a, new cost=400€).

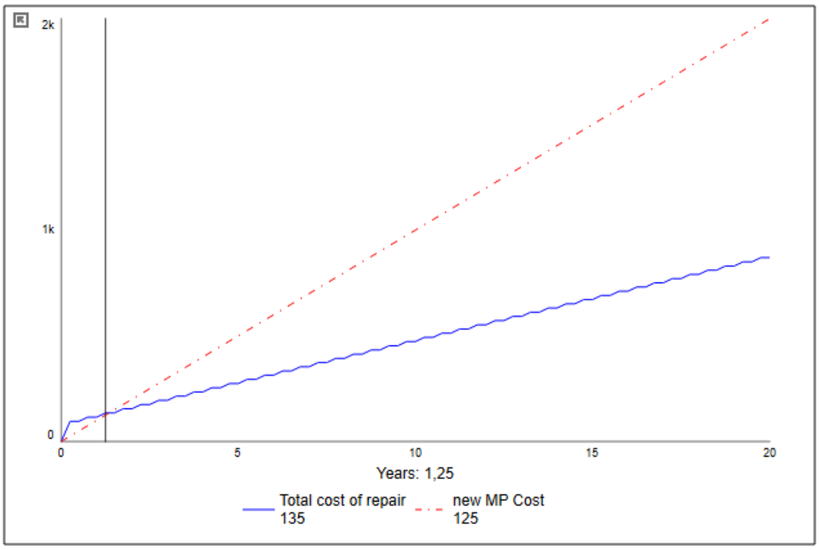


Fig. 26. Comparison of new mobile phone cost and repair cost by reusing phone over time (Repair cost =20€ /a, new cost=400€).

VII. Summary of Research Results

A draft version of the new lifecycle sustainability analysis model has been developed, which includes a qualitative representation of the model using CLD. The CLD helps describe the relationships among the components of the system. Through the CLD, specific actions and measures have been identified to reduce demand for cobalt and, consequently, address the issue of child labour in cobalt mines.

For instance, reducing the demand for cobalt can directly impact the reduction of child labour. Measures such as investing in battery technologies or cobalt recycling technologies can help decrease the demand for cobalt by exploring alternative sources or substitutes. Additionally, extending the lifespan of smartphones can also contribute to reducing the demand for cobalt. Furthermore, strong enforcement of child labour laws can be an effective measure in addressing child labour.

These identified measures should be further validated through modelling simulations using system dynamics. Simulations provide the ability to anticipate different future scenarios when implementing the mentioned measures, allowing for better decision-making, and understanding of their potential impact.

But to convert CLD into Stock and flow diagram for simulations, more data are needed. The measures identified by CLD, e.g., investment in cobalt-free or low-cobalt technologies, investment in cobalt recovery technologies, the reuse of cobalt-based Li.B. in portable devices, or how much the international financial support or local government support for the formalization of ASM mines, to solve poverty in DRC, are not available, e.g., due to business secrets, or political reasons.

Hence, the simulations presented in this paper focused on one specific measure, which is the reuse of smartphones, and examined how this action can influence the demand for cobalt. Although there was another simulation exploring the effects of relying on Li.B. or cobalt recovery, further continuation of this simulation requires sufficient real data.

By concentrating on the reuse of smartphones, the study aimed to understand the potential impact on cobalt demand reduction. However, it is important to note that the exploration of alternative measures and their effects on cobalt demand is an ongoing process that relies on the availability of reliable data. Continued research and data collection will enable a more comprehensive analysis of the effects of different actions on cobalt demand and sustainability.

Nevertheless, this study contributed to the state of the art by applying system dynamic modelling and simulation to sustainability. This study provided researchers with a new perspective for investigations into employing novel design toolsand simulation to analyse complex systems. Practitioners could benefit from a better understanding of issues of a product or industry. The proposed adapted DBMfS approach may help policymakers in the development of sustainability-related regulations.

The primary focus of this research was on the social dimension of sustainability, specifically within the smartphone industry. The aim was to examine the feasibility of the proposed conceptual method and framework. Through this investigation, various initiatives and practices were identified that are not aligned with the principles of sustainability within the electronics industry.

VIII. Conclusion and Future Work

Since not all data are available for building methodical equations, which are required for computer simulation, therefore this should be the focus of future work. An alternative option for the future, research can also apply qualitative methods to calibrate and simulate future actions, and development trends, which rely on experts' opinions, via survey.

System dynamics requires an intensive level of skills, resources (including financial, time, and personal) and motivation. On the theme of reducing demand for cobalt, and reducing child labour in the cobalt mining process, it is difficult for a one-man show to solve a complex problem. It is reasonable to imagine, that one organization be built for future work, to invest in cobalt demand & child labour issues; teams with expertise in smartphone eco-design, re-manufacturing, supply chain management, battery technologies, recycling technologies, human rights, etc. are needed, working together with local government and other stakeholders, to provide different probabilities for the future.

Nowadays, with models generated from data technology and advanced algorithms, data capture and interoperability, as well as the integration of machine learning and artificial intelligence algorithms, play crucial roles in understanding and optimizing the research in the global material lifecycle [39].

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