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Greening Foundation Industries: Shared Processes and Sustainable Pathways

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Abstract: Foundation industries, encompassing metals, ceramics, cement, paper, chemicals, and glass, play a vital role in driving industrial economies. Despite their pivotal role, a comprehensive understanding of shared processes and their impact on resource utilisation remains elusive. This study employs a novel approach, leveraging an adapted Dependency Structure Matrix (DSM), to unveil the core processes commonly utilised among these industries. These processes are then evaluated based on their influence on energy consumption and CO_2 emission. The investigation revealed 18 common processes categorised by their processing principles, their expected outcomes, and the equipment used. Remarkably, these processes emerge as significant contributors to both energy consumption and CO_2 emissions. Notably, pyroprocessing emerged as a prevalent practice in five out of the six sectors, while the production of dried products and crushers and mills were the most frequently encountered outcomes and equipment used, respectively. This paper discusses the implications of these findings for foundation industries, emphasising potential areas for enhancing manufacturing operations to reduce environmental damage and facilitate knowledge transfer among the various sectors. Furthermore, the study identifies shared abatement options that can be collectively implemented across industries to achieve more substantial reductions in environmental footprint. By identifying and prioritising the most impactful processes in foundation industries, this study provides a strategic footing for advancing sustainable and efficient manufacturing practices within these critical sectors.

Keywords: foundation industries; sustainable manufacturing; energy consumption; carbon emissions; resource utilisation

Citation: Sherif, Z.; Sarfraz, S.; Jolly, M.; Salonitis, K. Greening Foundation Industries: Shared Processes and Sustainable Pathways. *Sustainability* **2023**, *15*, 14422. https://doi.org/10.3390/su151914422

Academic Editor: Marcin Relich

Received: 31 August 2023
Revised: 21 September 2023
Accepted: 29 September 2023
Published: 1 October 2023

1. Introduction

Foundation industries (FIs), including metals, ceramics, cement, paper, chemicals, and glass, play a vital role in supporting industrial economies around the world. They are responsible for 59% of the total energy used by the manufacturing sector of the U.S. [1] and produce 75% of all materials used in the UK [2]. These industries provide essential materials and products that serve as building blocks for various sectors, such as construction, transportation, packaging, and energy generation [3]. However, the manufacturing industry, including FIs, faces significant challenges in terms of sustainability and resource utilisation. The growing concerns about climate change, resource scarcity, and environmental degradation have necessitated a re-evaluation of manufacturing practices to promote sustainability.

Sustainability, an imperative in today's world, is the cornerstone of responsible industry practices. It encompasses the balanced integration of social, economic, and environmental considerations. The triple bottom line (TBL), an influential concept introduced in 1997, evaluates the performance of organisations based on these three pillars [4], providing a holistic perspective that transcends singular metrics.

Therefore, sustainable manufacturing has grown into a prominent topic of discussion between business stakeholders around the world. This is attributed to the recognition of the urgency in advancing sustainable manufacturing due to the diminishing non-renewable resources, stricter regulations related to environment and occupational health and safety and increasing consumer preference for environmentally friendly products [5]. In this context, prioritising the environmental aspect of sustainability becomes imperative. The industrial sector in the UK accounted for 19% of primary energy equivalent consumption in 2019 [6] and a corresponding 14% of greenhouse gases (GHGs) [7]. Consequently, the analysis of manufacturing processes has witnessed increasing attention in recent years, with a particular focus on enhancing operational efficiency, conserving resources and reducing environmental impact.

Manufacturing processes in FIs are known to consume substantial resources and have a considerable impact on the environment. It is imperative to prioritise the environmental aspect in our pursuit of sustainable manufacturing practices to mitigate the ecological footprint of these crucial industries [8]. For instance, cement manufacturing accounts for 8% of global CO_2 emissions [9] and 7% of the global industrial energy demand [10]. This poses significant challenges to the industries' environmental sustainability and long-term viability [11]. Therefore, it is crucial to assess and enhance the energy performance and CO_2 emissions of these industries to align with the broader goals of sustainable development. The lack of comprehensive assessment and analysis of the most important manufacturing processes in FIs hinders progress towards sustainability [12,13].

Pertaining to that, while these industries share many common processes, without a clear understanding of the most critical processes driving environmental impact, it is challenging to identify and prioritise areas for improvement and implement sustainable practices effectively. Moreover, identifying commonality could foster knowledge exchange among sectors that may not typically interact. Several methods have been employed for analysing manufacturing processes and which have the potential to be used in identifying commonality, including Process Flow Diagrams (PFDs) [14], Life Cycle Assessment (LCA) [15], Material Flow Analysis (MFA) [16], and Natural Language Processing (NLP) [17].

While these methods offer valuable insights, they may have limitations in uncovering interdependencies and commonalities among processes. For instance, LCA assesses the environmental impacts of products or processes, potentially revealing common patterns [15]. Similarly, MFA involves tracking and quantifying the flows of materials through an economy or a specific system, possibly revealing shared material usage patterns [16]. However, their broader focus may restrict their effectiveness in pinpointing specific processing commonalities that are crucial for targeted knowledge transfer. Furthermore, PFDs provide a visual representation of the process flow, but they are limited in analysing complex interdependencies [14]. NLP, while capable of extracting information from unstructured text, may require significant preprocessing and may not be as specialised for manufacturing process analysis [17].

Among the available methods for examining manufacturing processes, it becomes evident that having a specialised approach designed explicitly for identifying commonality is crucial for efficiently uncovering shared processes and their interdependencies. This ensures that the analysis is precise and targeted towards identifying common aspects of the processes, enabling the sharing of environmental impact abatement options across industries. Such an approach should streamline the process of selecting the most impactful processes that warrant collective action, ultimately enhancing sustainability and resource efficiency within FIs.

Commonality, as a concept, has proven instrumental in resource planning. By comparing products or parts and identifying areas of commonality, organisations can streamline their resource allocation for improved efficiency [18]. This approach has been extensively explored in various literature. For instance, in the study by Collier [19], a systematic analysis was employed to examine the commonality of single end items, product families or entire product lines. This not only allowed for more targeted resource planning but also unveiled opportunities for standardisation and manufacturing cost reductions. Similarly, Heese and Swaminathan [20] conducted a comparative analysis of production components in the automotive industry. By identifying common components, they were able to suggest strategies for resource optimisation and quality improvements.

Despite its potential, it is noteworthy that no study has been reported that investigated the implications of this practice in revealing the commonality of manufacturing processes. This highlights a significant opportunity that this study aimed to explore. Accordingly, various methods have been recognised that primarily focus on identifying commonalities and dependencies within a system, making them well suited for the research goal. These methods include Hierarchical Clustering [21], Bayesian Networks [22] and Matrix Based Methods [23].

While these methods have shown promise in their respective domains, they may have limitations when applied to the specific context of identifying commonalities in manufacturing processes. For instance, Ahn and Chang have used Hierarchical Clustering to identify similarities in business processes, including manufacturing operations, at an operational level, for facilitating managerial activities and offering applications for process modelling and optimisation. However, it may not provide the granularity needed for detailed analysis of complex industrial processes [21]. Fradi et al. developed an approach for indexing 3D CAD models based on the similarity of their reusable sub-parts, using a Bayesian network. This enables efficient reuse of CAD data across different platforms. Nevertheless, challenges may arise when extending this approach to the intricate interdependencies within manufacturing processes [22].

On the other hand, Matrix Based Methods emerged as a particularly promising avenue [23]. Specifically, the Dependency Structure Matrix (DSM), a specialised technique explicitly utilised to represent and analyse interdependencies within a system, stands out [24]. Originally prevalent in the automotive sector for investigating the modularity of products, it has been adapted to identify commonalities across processes within FIs [25].

To utilise such a method, classifying the processes is essential for quantifying commonality. It allows for a methodical categorisation of manufacturing processes based on their technical and operational attributes. This classification serves as the basis for identifying similarities and overlaps across different processes within the FIs. Existing literature proposes various classification mechanisms for manufacturing processes which are normally for a particular purpose, such as process selection [26,27]. These are often specific to individual sectors, such as metal machining and joining [28] and ceramics restorative materials [29] or a specific type of production, such as additive manufacturing [30]. Conversely, classifications are too generic to be useful, for example, by classifying according to the nature of the process in terms of chemical or physical change [31]. A comprehensive universal classification system applicable across all sectors is lacking.

This research addresses these critical gaps by identifying and evaluating the most significant common processes within FIs. By employing an adapted DSM, a structured procedure is developed to assess and quantify process commonality. This methodical examination, considering energy and emissions implications, provides a clearer understanding and forms the basis for targeted decision-making and efficient resource allocation for sustainability enhancements. Stakeholders can prioritise actions and allocate resources for the greatest sustainability improvements considering significant processes. Furthermore, this research opens avenues for collaboration and knowledge sharing among different sectors, fostering a cross-industry dialogue and collective effort towards sustainable manufacturing practices.

Since the manufacturing industry is a significant contributor to resource consumption and environmental degradation, sustainable manufacturing practices can lead to increased operational efficiency, reduced waste generation, and lower resource consumption, thereby improving the economic viability and competitiveness of manufacturers [32]. Moreover, by adopting sustainable practices, the manufacturing industry can contribute to several

Sustainable Development Goals (SDGs) [33]. SDG 9 emphasises sustainable industrialisation and technological advancements, which aligns with the identification of areas for improvement and adoption of best practices in sustainable infrastructure and manufacturing processes. SDG 12 focuses on responsible consumption and production, and the evaluation of resource utilisation and environmental impact contributes to identifying opportunities for resource efficiency within FIs. Additionally, this research supports SDG 13's aim of combating climate change by assessing environmental implications and identifying opportunities for reducing emissions and energy consumption.

In summary, this research addresses the gap in understanding the significance of common manufacturing processes in FIs. Identifying and evaluating these processes promotes sustainability by informing decision-making, prioritising actions, and fostering collaboration among sectors. Ultimately, this research intends to enhance the environmental performance of FIs and advance sustainable manufacturing practices for a greener future.

2. Methodology

This section outlines the methodology employed in this study to identify common processes as well as analyse their emissions and resource utilisation. The methodology encompasses steps incorporating industry selection, process mapping, commonality evaluation, process analysis, and identification of abatement options. By following this systematic approach, the research aims to provide valuable insights into the common processes, their impact, and the potential for implementing best practices to enhance sustainability and energy utilisation across the FIs.

2.1. Industry Selection

The selection of industries is a key first step in this research. Each of the sectors under consideration comprises various products, and for each product, there may be different production routes. The approach needed to allow for capturing the processes that are most representative of the industry's overall energy utilisation and environmental emissions. Therefore, to manage the extensive number of products and routes within each sector, a filtration process is employed. One product is chosen from each sector to perform this exercise as a proof of concept. This is accomplished by identifying the most widely produced products within each sector and then selecting the most commonly used production route for those products.

By focusing on these key products and their associated production routes, the study aims to provide a comprehensive understanding of the processes exerting the most significant influence on the industry's overall energy utilisation and environmental emissions. Additionally, this selection process aligns with industry practices, mirroring the emphasis placed on high-volume, widely produced products and their corresponding production methods. This methodology not only reflects real-world industrial operations but also enhances the practical applicability and relevance of the findings for stakeholders in the FIs.

2.2. Process Mapping

The subsequent stage is creating process maps, a crucial step in comprehending the distinct stages within the production cycle of the chosen products. This is accomplished by visually delineating the primary production processes spanning from raw material preparation to finishing, as illustrated in Figure 1. Furthermore, the step involved quantifying the energy consumption and CO_2 emissions associated with each process. This aided in determining their relative significance in terms of resource utilisation and environmental impact. This clarification facilitates the assessment of the respective importance of the main production steps, thereby establishing the basis for subsequent analysis and comparison.

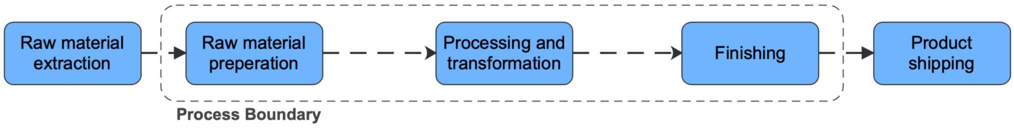


Figure 1. Process mapping boundary.

2.3. Commonality Matrix

The development of a commonality matrix is essential for identifying and understanding the shared processes across the selected sectors. DSM, a technique utilised to investigate the modularity of products [24], has been adapted to identify commonality across FIs' processes. A template is shown in Table 1. Additionally, by creating a three-tier classification system based on processing principle, outcome, and equipment, a framework is established for comparing processes across sectors (principle = 1, output = 2, and equipment = 3). In more detail, process commonality is firstly assessed in terms of the principle of the underlying concept or method employed in a manufacturing process, representing the fundamental approach or technique deployed. Secondly, it is evaluated on the outcome, desired result or objective achieved through the manufacturing process which represents the end product or the specific goal that the process aims to accomplish. Lastly, the commonality is considered in terms of equipment, which refers to the machinery, tools, and devices used in the manufacturing process [31,34,35]. Such information can facilitate knowledge transfer and collaboration among sectors.

Table 1. Commonality matrix template.

Principle	1	Process A	Process B	Process C	Process D	Process E
Outcome	2					
Equipment	3					
Sector A	Process A					
	Process B					
	Process C					
	Process D					
	Process E					

2.4. Process Analysis

The process analysis step builds upon the commonality matrix to further examine the identified common processes. Scoring the commonality tiers allows for prioritising the most prevalent and significant processes in terms of their commonality across sectors. This provides insights into the critical areas where collaboration and knowledge sharing can yield the greatest sustainability improvements. Additionally, by listing the top thermal and electrical energy-intensive processes, as well as the top CO_2 emitters, the correlation between intensity and commonality can be explored, identifying potential areas where significant energy efficiencies and emission reductions can be achieved.

2.5. Abatement Options

The final step involves identifying various abatement options for the common processes identified in the previous steps. This involves looking into best practices and emerging technologies tackling energy and emissions of processes. The aim is to determine whether an option available for a specific process in one industry can be applicable and beneficial for another industry. This approach promotes the adoption of proven and effective practices that have already demonstrated benefits in other sectors.

To sum up, the methodology encompasses a systematic approach to address the research aim. The selection of industries and processes, coupled with process mapping, commonality analysis, process analysis, and identification of abatement options, provides a comprehensive understanding of resource utilisation and opportunities for improvement within the FIs. The methodology ensures a rigorous and structured approach to generate valuable insights for manufacturers, policymakers, and other stakeholders, facilitating the transition towards sustainable manufacturing practices.

3. Results

This section presents and discusses the key findings from the material and route selection process, commonality matrix analysis, and identification of abatement options. It provides valuable insights into production characteristics, energy utilisation, CO_2 emissions and opportunities for sustainable manufacturing practices within the studied sectors.

3.1. Material Selection and Process Mapping

The product and route selection process for each sector revealed important insights into the production characteristics and environmental implications within the respective industries. The product selection process was based on global production data or major producing country production volumes, depending on the availability of data. Regarding route selection, the most popular production method is selected for the analysis.

3.1.1. Metals

Steel emerged as the dominant metal in terms of production volume, driven by its versatile applications across industries such as construction and manufacturing. With a global production volume of 1958 million metric tons (Mmt) in 2021 [36,37], steel production exceeded the second-ranked metal, aluminium, by a significant margin (30 times more) as presented in Figure 2a. For steel production, the primary route selected was the BF BOF (Blast Furnace-Basic Oxygen Furnace) method. This choice was influenced by the method's widespread use and popularity in the industry, representing 70% of global steel production [38]. However, it is important to note that although the electric arc (EAF) method is known for its environmental friendliness [39], its viability is dependent on the availability of scrap steel.

3.1.2. Glass

Among the various types of glass, container glass emerged as the dominant product in terms of production. As shown in Figure 2b, glass containers accounted for approximately 45% of global glass production in 2018 [40], highlighting their significant contribution to the industry. This high production volume can be attributed to the extensive use of glass containers in packaging applications, such as bottles and jars. Regarding the route selection for glass production, the press and blow method was identified as the predominant and commonly used technique [41]. This method involves the formation of glass containers by pressing molten glass into moulds and then using compressed air to blow the glass into the desired container shape [42]. It has gained popularity due to its efficiency and versatility in producing a wide range of container designs and sizes.

3.1.3. Chemicals

Among bulk chemicals, plastics have taken the lead as displayed in Figure 2c, with approximately 43% of chemicals produced in the U.S. (2nd largest chemical producer) in 2019 being exclusively plastics [43], indicating their pivotal role in various industries such as packaging, construction, and automotive. The remaining 57% of chemical production primarily comprised ammonia, sodium hydroxide, and chlorine, among other products that could be used as constituents for plastic manufacturing. In terms of route selection, the focus was placed on the production of olefins, which serve as fundamental building blocks for plastics. The steam cracking method was identified as the primary process for olefin production, renowned for its vital role and elevated energy intensity within the petrochemical industry due to its highly endothermic nature [44]. Around 98% of the global production of ethylene is carried out in steam crackers which is the feedstock for polyethene (PE) plastic, the most commonly produced plastic [45], with the dominant feedstock for worldwide ethylene production being naphtha (55%) [46]. The steam cracking method involves the thermal decomposition of hydrocarbon feedstocks, typically derived from crude oil or natural gas, to yield olefins like ethylene and propylene, which are extensively used in plastic manufacturing [47].

3.1.4. Ceramics

In the ceramics sector, ceramic tiles were identified as the most energy-consuming product to produce. The tiles industry accounted for nearly 31% of the EU total production value within the ceramics sector signified by the global production of 18 billion m^2 [48–50] as presented in Figure 2d. This highlights its significant energy demand compared to other ceramics products. Regarding the route selection for ceramic tile production, the pressing method was identified as the primary and prevailing technique employed in the industry. This method involves the use of pressure to shape and form ceramic tiles from clay or other ceramic materials [51].

3.1.5. Paper

Packaging paper stood out as the predominant type of paper, accounting for a substantial 63% of global production in 2021 [52], as shown in Figure 2e. This significant share can be attributed to the increasing demand for packaging materials, especially in the rapidly expanding e-commerce and consumer goods sectors. In terms of route selection, the widely adopted kraft pulping method was chosen for paper production. This method represents the prevailing industrial trend in global paper manufacturing [53]. The kraft pulping process involves the chemical breakdown of wood fibres using a combination of heat, chemicals, and mechanical action. This technique is known for its efficiency in extracting cellulose fibres and removing impurities, resulting in high-quality pulp suitable for producing various types of paper, including packaging paper [53].

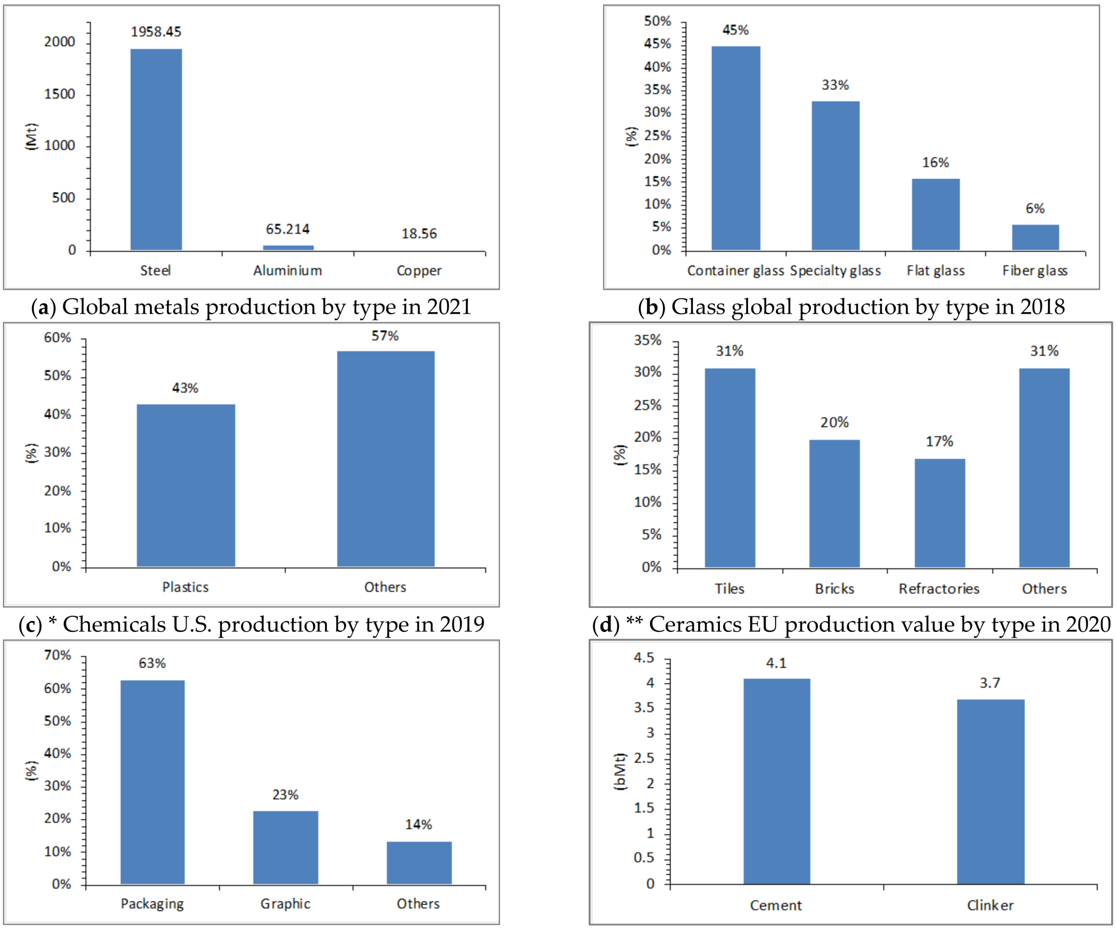
3.1.6. Cement

In terms of product selection, cement products are distinguished by the ratio of clinker to other additives or aggregates in their formulation, which can range from 100% to 20%. Globally, clinker production accounted for a substantial 90% of the total cement produced in 2021 [54] as portrayed in Figure 2f. This high proportion of clinker highlights the industry's significant environmental impact, as clinker production is known to be energy-intensive and releases considerable carbon dioxide emissions [55]. Regarding route selection, the dry method was identified as the primary production route for cement. The dry method was chosen based on its popularity and favourable energy consumption characteristics [56]. In this method, raw materials such as limestone and clay are blended, pulverized, and then subjected to kiln firing. The dry method has gained prominence in the industry due to its energy efficiency and relatively lower environmental emissions compared to other cement production methods [57].

In summary, this section focused on product selection within the 6 industries. The product selection process involves using global production data or major producing country volumes to determine the main products. For route selection, the prevalent production method is analysed. Figure 3 showcases the main products and production routes across the six FIs as well as highlighting the selected ones using a tick mark.

3.1.7. Process Maps

Following the product and route selection, process maps were created to track the production cycle from raw material preparation to processing, transformation, and finishing stages in each industry as presented in Figure 4. In total, 37 processes have been identified. This information laid the foundation for further analysis, evaluation, and exploration of common processes and their energy and environmental implications.



(**a**) Global metals production by type in 2021

(**b**) Glass global production by type in 2018

(**c**) * Chemicals U.S. production by type in 2019

(**d**) ** Ceramics EU production value by type in 2020

(**e**) Paper global production by type in 2021

(**f**) Cement and clinker global production in 2021

Figure 2. Global and regional production by product type for selected sectors. (**a**) Metals, (**b**) Glass, (**c**) Chemicals, (**d**) Ceramics, (**e**) Paper and (**f**) Cement. * Chemical production values are taken from the U.S. which is the second largest chemicals producer. ** Ceramic production values are taken from the EU which is the second largest ceramics producing region. The results are compiled from [36,37,40,43,48–50,54].

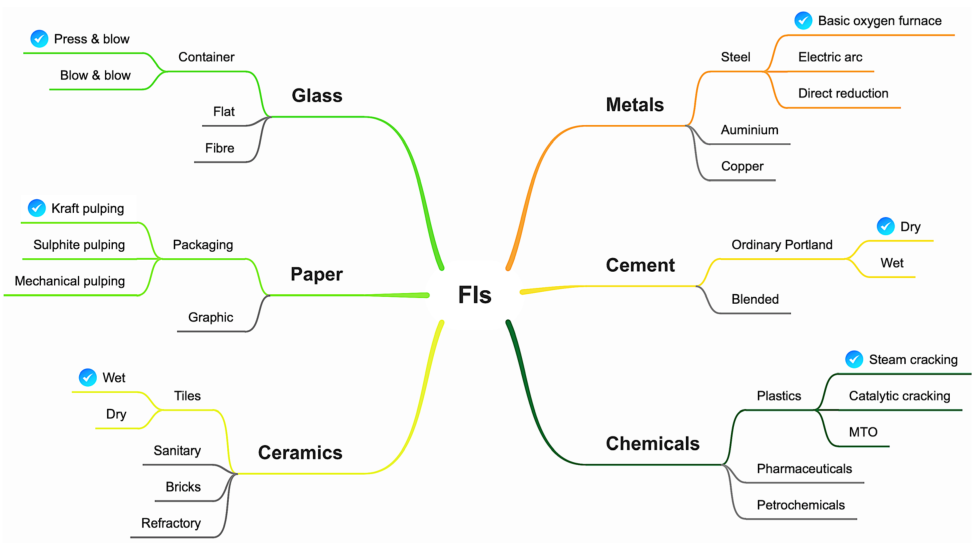


Figure 3. Identified main products and production routes across the 6 foundation industries.

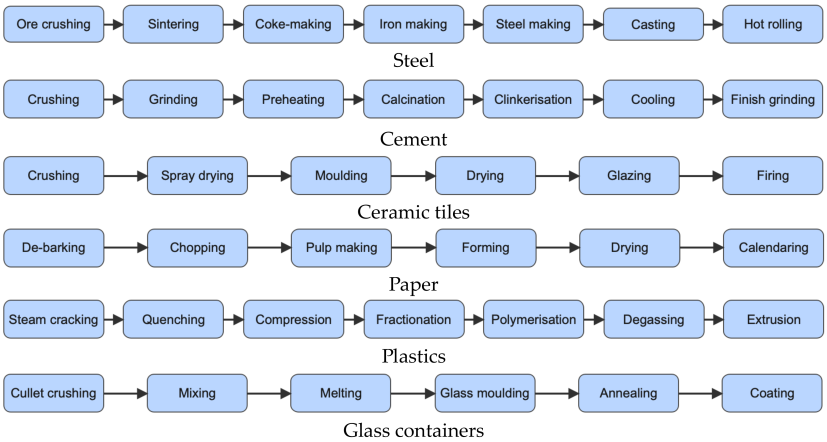


Figure 4. Process flow map for the selected products within the 6 foundation industries [39,58–61].

3.2. Commonality Matrix

This step was instigated by classifying the production processes of the selected products using the three-tier method. In which the processes are depicted in terms of their principle, the outcome and the equipment used. The classification of processes is presented in Table A1 in Appendix A.

The commonality matrix was developed to analyse the shared processes across the studied industries. The subsequent phase included populating the matrix where the identified 37 processes are placed both vertically and horizontally, as presented in Figure 5. Each process is rated against others in terms of common principles, outcomes, and equipment. A score of 1 is assigned for common principles, 2 for common outcomes, and 3 for common equipment, while 0 represents no commonality. The scores are presented by a color scale in the figure. This scoring system allowed for an assessment of the level of commonality among the processes. The matrix provided a visual representation of the interconnections and similarities between processes across the different industries, highlighting the areas of overlap and potential collaboration.

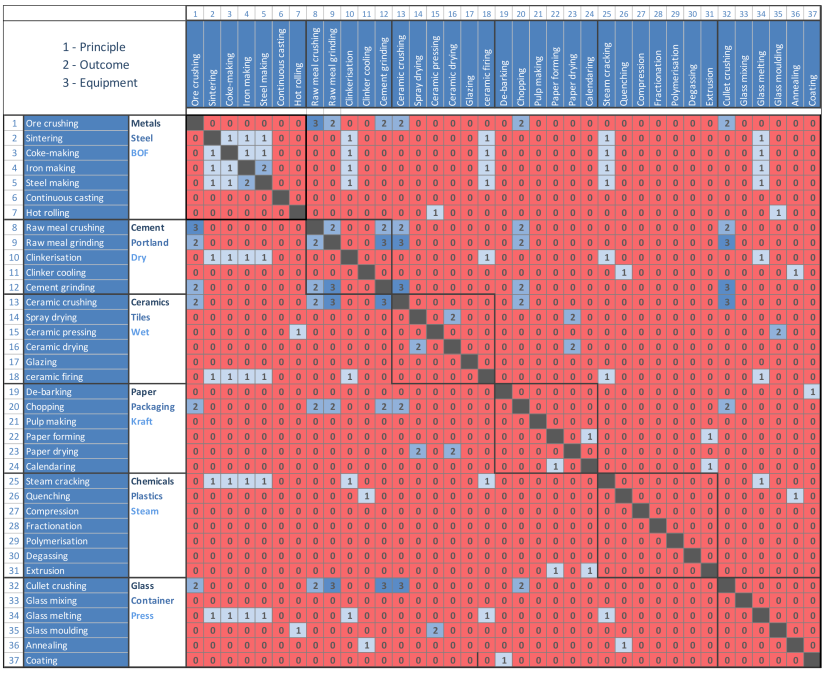


Figure 5. Commonality matrix.

3.3. Processes Analysis

Out of the 37 processes investigated, 18 were identified as common processes based on the three aspects of principle, outcome, and equipment. All of which ranked among the top intensive processes in terms of both electrical and thermal energy consumption as well as CO_2 emissions, highlighted by tick marks in the results presented in Table 2. This emphasises the diverse energy demands and environmental impacts of these processes. Moreover, the possible size of the prize that could be acquired by sharing knowledge across sectors.

Table 2. Top common processes energy and emissions intensiveness analysis, data acquired from [57,61–72].

Process	Electrical Energy GJ/t	Top Electrical Consumer	Thermal Energy GJ/t	Top Thermal Consumer	CO_2 Emissions kg/t	Top CO_2 Emitter
Ore crushing	0.11	✓	0		0	
Raw meal crushing	0.12	✓	0		0	
Ceramic crushing	0.168	✓	0		0	
Cullet crushing	0.5	✓	0		0	
Raw meal grinding	0.1	✓	0		0	
Cement grinding	0.169	✓	0		0	
Chopping	0.37	✓	0		0	
Iron making	0.09		12.85	✓	1219	✓
Steelmaking	0.09		−0.26		282	✓
Sintering	0.1	✓	1.37	✓	200	✓
Coke-making	0.09		3.82	✓	794	✓
Clinkerisation	0.007		2.9	✓	580	✓
Ceramic firing	0.2	✓	2.85	✓	147	✓
Steam cracking	1	✓	12.5	✓	1600	✓
Glass melting	0.38	✓	4.39	✓	318	✓
Spray drying	0.113	✓	1.22	✓	89	✓
Ceramic drying	0.01		0.33	✓	21	✓
Paper drying	0.58	✓	5.4	✓	250	✓

Regarding the commonality of principles, Pyroprocessing, in which materials are subjected to high temperatures to instigate a chemical or physical change, emerged as predominantly common, found across all sectors except for paper. This indicates its widespread application and importance in various industries. On the other hand, the most shared outcome was the production of dried products, a recurring theme observed in both ceramics and paper sectors in which moisture is removed from intermediate products. Furthermore, reduction in material size, an outcome that requires mechanical force to facilitate handling and processing, occurred in all industries except chemicals. In terms of machinery, crushers and grinding mills were identified as the most frequently utilised equipment, prominently featured in all industries except chemicals and paper. Their prevalence underscores their crucial role in these sectors and their significant impact on environmental impact. The 18 processes along with their corresponding aspects are illustrated in Figure 6.

Practitioners across different sectors should take note of the identified common processes, as they represent critical areas where collaborative efforts and knowledge-sharing could lead to substantial efficiency gains. By leveraging shared insights and best practices, practitioners have the potential to significantly reduce resource consumption and environmental footprints in their respective industries. For researchers, these findings highlight the need for further investigations into specific technologies and strategies that can enhance the sustainability of these common processes. Exploring innovative approaches to improve the energy efficiency and environmental performance of these intensive processes could yield breakthroughs that benefit not only individual industries but also contribute to broader sustainability goals.

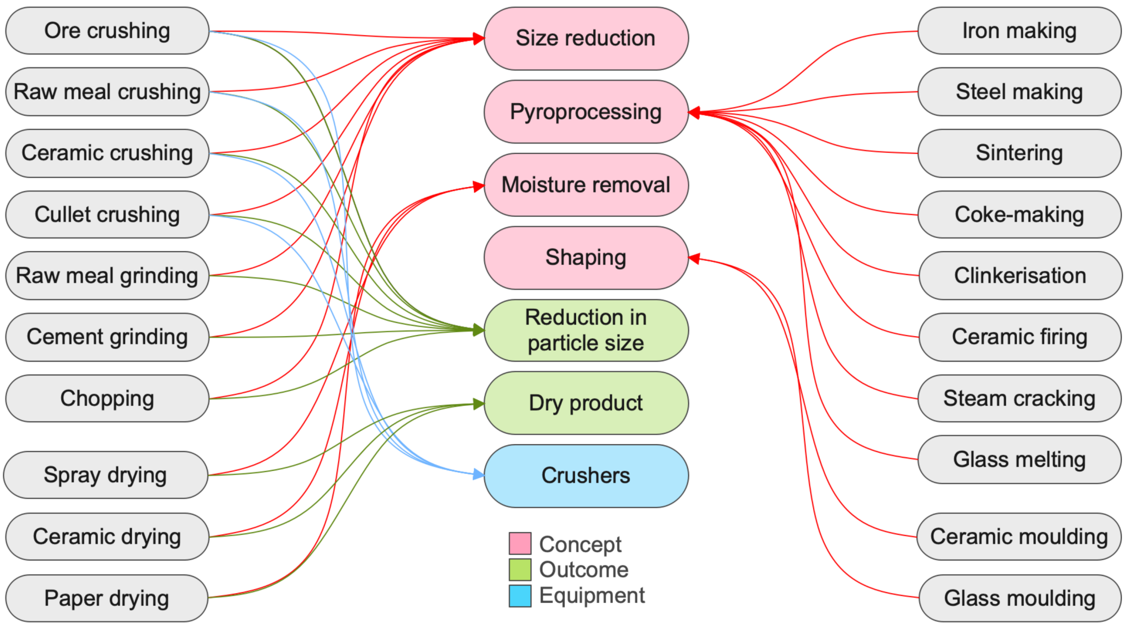


Figure 6. Common processes and their associated common principles, outcomes, and equipment.

3.4. Abatement Options

3.4.1. Pyroprocessing

Pyroprocessing is a major processing technology in the FIs. With high heat input being a major requirement in manufacturing but also a source of concern due to the high energy required, multiple actions are stated to mitigate the energy consumption of such a process. These are available as different features targeted to each industry or technology. For instance, a Blast furnace could benefit from pulverised coal injection resulting in a 3.6% energy reduction [73]. On the other hand, altering steam flow rate and cooling water temperature reduces the energy consumption of steam crackers by 13% [74]. However, a few improvements could also apply to more than one industry. A preheating tunnel in steel production can save up to 0.22 GJ/t of energy [75]. In cement, a 6-stage preheater can save up to 1.27 GJ/t of energy compared to a 1-stage preheater [66]. The preheating of glass prior to melting however has only recently gained traction despite its energy-saving potential [76,77]. Another aspect encompassing pyroprocessing is surface heat loss. Insulation plates on glass melting furnaces reduce thermal losses [78] while improving cement kiln refractoriness can save up to 0.6 GJ/t of thermal energy [57]. Furthermore, heat recovery technologies can be employed to convert waste heat into useful energy. It does not reduce the pyroprocessing energy specifically, but since the recovered energy could be utilised elsewhere in the process, it lowers the overall energy consumption per unit product. It has been used in cement kilns to recover up to 5% of waste heat [79]. It has also been recorded in blast furnaces, improving efficiency by 3.1% [80] and in ceramics firing kilns in which efficiency was improved by 11% [81]. Moreover, increasing evidence demonstrates that transitioning from fossil fuel consumption to electric technologies reduces both costs and emissions [82]. In the scenario of firing ceramics, furnace electrification could be a viable alternative for reducing gas emissions, especially for large kilns producing bricks and tiles [83,84]. During cement manufacturing, switching from a coal-fired calciner system to an electrically powered calciner can lead to a reduction of 78% in CO_2 emissions [85]. However, the prominence of electrification comes into play when the source of electrical energy is derived from renewable sources. These findings indicate a need for a thorough analysis of intersected practices and their applicability to be functional to other sectors.

3.4.2. Drying

The drying of intermediate products is one of the most energy-intensive processes. 67% of the total energy required to produce paper [86] and 45% of ceramics production energy [87] is due to drying. In the case of paper drying, it is conventionally accomplished by a steam-heated roller. Enhancing heat recovery techniques for the heated rollers can lead to a potential 16% decrease in energy usage. This outcome corresponds to a consequent reduction of 12% in emissions [88]. Furthermore, emerging technologies in microwave drying have shown energy reductions of up to 12% [53]. A similar trend has been observed in the ceramics industry where infrared has been successfully used to dry ceramics with 4 times less power [89].

3.4.3. Crushing and Grinding

Fine particle size is crucial to enable smooth handling and subsequent production stages like burning or mixing. Cement raw material crushing and grinding represents a significant portion, accounting for 71% of the total consumed electrical power [57]. The adoption of vertical roller mills in raw material grinding has demonstrated a notable reduction of 25% in energy consumption and a 57% decrease in CO_2 emissions compared to traditional ball mills [90,91]. For raw material crushing, cone crushers are identified as more efficient than other alternatives [92]. However, there appears to be a limited focus on new or emerging technologies specifically aimed at further reducing energy consumption in these processes.

4. Conclusions and Future Work

Foundation industries play a pivotal role in global manufacturing, providing essential materials for various sectors. To enhance sustainability and resource efficiency, this study delved into the commonality of processes across different sectors. The research involved a thorough examination of 37 processes, assessing their principles, outcomes, and equipment. By using an adapted DSM, 18 processes were identified as common across the 6 sectors in question which were further analysed based on their energy and CO_2 emission intensities.

The key findings shed light on the prevalence of these processes as well as accentuate the diverse energy prerequisites and environmental consequences of these operations. Furthermore, it highlights the potential significant benefits achievable by cross-sector knowledge sharing. Pyroprocessing emerged as a prominent principle, widely applied across most sectors except paper. Additionally, the production of dried products was a common outcome observed in the ceramics and paper industries. Crushers and grinding mills were identified as frequently utilised machinery.

Additionally, various abatement options have been identified to address energy consumption and CO_2 emissions associated with these common processes. These options range from efficient heat recovery systems to the utilisation of alternative fuels and electrification. Interestingly, certain sectors seem to have more mature solutions in place for tackling these challenges, while others have not extensively explored these strategies. This discrepancy underscores the valuable cross-sector knowledge exchange that could take place. By sharing successful practices and technologies across industries, sectors can accelerate their sustainability efforts and reduce the need to reinvent solutions already in existence. This cooperative approach could lead to more efficient adoption of established technologies, ultimately contributing to a greener industrial landscape.

The findings align with the Sustainable Development Goals (SDGs), supporting sustainable industrialisation, responsible consumption and production, and climate action. This analysis equips stakeholders with valuable information to allocate resources effectively, prioritise improvement efforts, and adopt sustainable practices. Furthermore, it offers a basis for benchmarking and best practice adoption, driving the industry's transition towards sustainable manufacturing.

Future work could extend the analysis to encompass all products within each sector, exploring additional potential knowledge exchange opportunities among industries. Furthermore, by incorporating additional layers, such as considering process mechanisms, and additional environmental impacts, such as wastewater, the potential for unveiling further shared characteristics is amplified. Beyond that, Exploring the economic aspects of shared processes and resource allocation across different sectors will provide valuable insights into potential cost-saving opportunities and improved resource efficiency. This avenue of research can shed light on how collaborative efforts and knowledge sharing can not only enhance sustainability but also lead to economic advantages for the industries involved. This holistic approach will streamline the identification of optimal practices, nurturing sustainable methodologies across diverse sectors.

Author Contributions: Conceptualization, K.S., Z.S. and S.S.; methodology, Z.S.; writing—original draft preparation, Z.S.; writing—review and editing, K.S. and S.S.; supervision, K.S. and M.J.; funding acquisition, K.S. and M.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by UK Research & Innovation (UKRI), Grant Reference: EP/V054627/1.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data supporting this study are provided in full in this paper.

Acknowledgments: The authors would like to thank the TransFIRe (Transforming Foundation Industries Research and Innovation Hub) for their support of this work.

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

Appendix A

Table A1. Classification of the identified processes.

	Process	Concept	Outcome	Machinery
1	Ore crushing	Size reduction	Reduction in particle size	Crusher
2	Raw meal crushing	Size reduction	Reduction in particle size	Grinding mills, ball mills
3	Ceramic crushing	Size reduction	Reduction in particle size	Crusher
4	Cullet crushing	Size reduction	Reduction in particle size	Crusher
5	Raw meal grinding	Size reduction	Reduction in particle size	Crusher
6	Cement grinding	Size reduction	Reduction in particle size	Grinding mills, ball mills
7	Chopping	Size reduction	Reduction in particle size	Chipper
8	Iron making	Pyroprocessing (reduction)	Molten product	Blast furnace
9	Steelmaking	Pyroprocessing (oxidation)	Molten product	Basic oxygen furnace
10	Sintering	Pyroprocessing (Solid-state)	Agglomeration of ores	Sinter strand
11	Coke-making	Pyroprocessing (decomposition)	Decomposition of raw materials	Coke oven
12	Clinkerisation	Pyroprocessing (Solid state)	Sintering of intermediate product	Rotary kilns
13	ceramic firing	Pyroprocessing	Sintering and densification	Furnace
14	Steam cracking	Pyroprocessing (pyrolysis)	Decomposition of raw materials	Cracker furnace
15	Glass melting	Pyroprocessing	Molten product	Furnace
16	Spray drying	Moisture removal	Dry Intermediate product	Spray dryer
17	Ceramic drying	Moisture removal	Dry Intermediate product	Dryers
18	Paper drying	Moisture removal	Dry Intermediate product	Steam dryer
19	Ceramic moulding	Shaping	Formation of shape	Pressing machines
20	Glass moulding	Shaping	Formation of shape	Moulding machine
21	Hot rolling	Shaping	Plastic deformation	Rolling mill
22	Clinker cooling	Temperature reduction	Cooling of intermediate product	Air coolers
23	Paper forming	Forming	Formation of shape	Fourdrinier
24	Calendaring	Forming	Sheet formation	Calendars
25	Quenching	Temperature reduction	Gas stabilisation	Heat exchangers

Table A1. *Cont.*

	Process	Concept	Outcome	Machinery
26	Extrusion	Forming	Pelletised product	Extruder
27	Annealing	Temperature reduction	Strengthened product	Lehr oven
28	De-barking	Surface treatment	Decontaminated raw material	Drum debarker
29	Coating	Surface treatment	Hardened product	Sprayer
30	Continuous casting	Solidification	Solidified product	Ladle, tundish, mould
31	Glazing	Surface coating	Decorated layer	Printers
32	Pulp making	Delignification	Processed intermediate product	Cooking digester
33	Compression	Pressurisation	Increase pressure	Compressors
34	Fractionation	Co-products separation	Isolation of individual products	Fractionating columns
35	Polymerisation	Radical polymerisation	Polymer formation	Polymerisation reactor
36	Degassing	Degasification	Quality enhancement	Degasser
37	Glass mixing	Homogenization	Raw material mixture	Blender

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