

34th CIRP Design Conference

A Conceptual Assessment Framework for Sustainability in the Foundation Industries

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Abstract

Foundation industries in the UK are in constant pursuit of better technological solutions to enhance materials conversion efficiency and supply chain economies of scale. However, sustainable materials and strategies to conserve resources and better utilize waste streams tend to be ever more challenging to achieve when technological advances fall short in being widely adoptable by companies. Knowledge and technology transfer across multiple companies within the same sector (for example, construction materials production) or across seemingly common core processes (such as size reduction or furnaces) must be achieved for sustainability efforts to achieve economies of scale. Part of the reason why this is a difficult endeavor is the lack of visibility of the steps and drivers involved in a circular economy context with a view to achieve scale. Materials and technologies that could help foundation industries become more sustainable are being examined through the introduction of a novel framework that could help companies and policy makers understand where the opportunities exist. In this paper, the authors describe the design and development of the framework and offer examples drawn from an ongoing research and innovation project in foundation industries.

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Peer-review under responsibility of the scientific committee of the 34th CIRP Design Conference

Keywords: foundation industries; sustainability assessment; scalability; technology transfer

1. Introduction and context

Foundation industries, including steel, cement, glass, ceramics, and chemicals, are crucial to the global economy as they provide essential materials for various sectors.

Nomenclature

CE	Circular Economy
UKRI	United Kingdom Research and Innovation
TF	Transforming Foundation Industries Research and Innovation Hub (TransFIRE project)
SFS	Spent Foundry Sand

These industries are also significant contributors to environmental degradation due to their high energy consumption and waste creation. [1]. Therefore these industries are vital for a move towards a global circular economy, given their environmental footprint and central position across supply networks [2]. By applying circular economy strategies, these industries could reduce environmental impact while creating economic opportunities [3]. Circular economy strategies tailored to foundation sectors include: industrial symbiosis to re-use waste and by-products as circular inputs, product and process redesign for durability, reusability, upgradability [4], renewable energy and electrification [5], investing in recycling and remanufacturing capabilities [6] and exploring alternative materials like green hydrogen and bio-based polymers [7]. Enablers of a transition as such, like collaboration [2], 2014),

policy incentives [8], access to finance [9], and standardization [10] are critical for effective implementation.

1.1. The TransFIRE project (TF)

In this broader sustainable manufacturing context, the UK's Research and Innovation agency (UKRI) created the Transforming Foundation Industries challenge fund and set a number of projects in motion to deliver the blueprints (technologies, know-how, new materials, new knowledge) of their vision [2]. The Transforming Foundation Industries Research and Innovation Hub (TF) is one of the projects in this challenge fund and takes a multidisciplinary approach to creating the benefits for the Foundation Industries economy (valued at £52b p.a.) [2]. In this article the authors' intention is to better understand how TF project outputs could be used at scale by companies in the foundation industries sector, with a view to enable better policy interventions in the short and medium term.

Due to high cost of capital projects required to deliver significant changes in environmental performance, in combination with the associated high risk of adoption of technological innovations, there is considerable resistance to change from industry without significant and diverse industrial policy interventions [11]. These interventions can be guided by a set of tools and methodologies that encompass multiple scientific disciplines and have been developed as a cohesive toolkit focused on change facilitation for energy and material intensive industries [11, 12].

All authors in this article are involved with the project management and delivery of various outputs in the project, which started in 2021 and finishes in 2024. Approximately 100 companies have been recruited to support and get involved in various research and development activities. Confidentiality agreements are in place for certain aspects of research outputs, but most of the project outputs are shared publicly through UKRI and within the project community in pursuit of wider adoption of new knowledge and best practice.

This article is developed to become a resource for industrial policy makers and UKRI officials and thus is taking a tool design approach to the TF context and outputs as per Moultrie et al [13]. By following a design approach, this study can be more relatable to its audience (UKRI, researchers and industry). In performing this study, the authors reviewed literature in three areas of interest to the sustainability of foundation industries: a) new product development strategies/approaches, b) economic drivers for circular economy and sustainability and c) assessment models of in-house capabilities that enable better environmental performance. The literature review led to the design of a conceptual framework that is then used in a brief case study, to understand its usability and how project outputs could be adopted by different companies.

2. Literature review

In this literature review the intention is to identify interrelated concepts and models on sustainable manufacturing that have been used or can be used to better understand how

foundation industries can progress in terms of meeting net zero and related targets through technological solutions that stem from research projects. One of the search challenges is the term “foundation industries” which is relatively new and is used as an umbrella term by UKRI for companies that are primary and heavy users of energy and materials, making large volume, everyday items like glass, paper, cement, metals, chemicals and ceramics. Alternative ways of identifying literature related to these industries is “process” industries as well as “energy intensive” industries.

Several recent articles (2017-2023) have been identified through Scopus search, using a snowballing technique within articles related to these keywords: “sustainability”, “product design”, “circular economy”. The search then expanded on the identification of studies that synthesized tools, models and frameworks, that offer a multi-dimensional view/analysis in assessing or evaluating changes within the context of circular economy and changes at process and product level in industry.

The literature is segmented in three key sections reflecting literature search findings about: the connection between product development (new or existing product lines) and circular economy strategies, economic drivers for change in foundation industries and how in-house manufacturing/process capabilities are considered in planning for improvements at facility/factory systems level (process eco-efficiency and management systems as per Litos et al.) [14].

2.1. Circularity strategies in product development in foundation industries

Several articles are concerned with product development processes and strategies, either for new product introduction or improving an existing product's performance. Product development approaches can be clustered around four themes related to: narrowing, regenerating, slowing, closing of energy and material flows in industry [15]. There is also an evident thread in the literature on product eco-design that could inform companies about design attributes, environmental benefits and product qualities that align with sustainability objectives [16], [17]. In the context of foundation industries the concepts of industrial symbiosis and waste exchange [18], recycling heat, emissions and materials back into the process directly or post-consumer use phase [19, 20, 21] are primary strategies that take into account proximity of materials and energy flows to the core process in order to achieve profitable production rates [18, 22, 23].

By considering the concepts of managing energy and material flows against the four strategies by Aguiar and Jugend, an obvious next step is to consider the economic drivers behind different options, due to geographical and supply chain constraints [15].

2.2. Economic drivers for circularity in foundation industries

As per Andersen (2007) and Mathews and Tan, (2011), the idea of the circular economy is still largely confined to consideration of physical flows, and the economic drivers (and inhibitors) of eco-industrial initiatives have yet to receive sufficient attention [24, 25]. A range of economic drivers and

indicators can be used in the context of transforming foundation industries to help researchers, funders and policymakers understand where the opportunities for individual companies and sectors may exist [10, 26, 27, 28, 29] such as:

- transportation cost savings
- resource efficiency and recovery rates
- enhanced circularity rates
- competitiveness
- raw materials dependencies (price, availability, etc.)
- access to new markets and revenue streams
- product quality improvements
- processing time
- global warming potential
- energy consumption
- landfill and taxation

Some of the drivers above are connected with the wider socio-economic context, where companies have production sites (e.g. competitiveness) and therefore their ability for influence is limited. Some others however are more related to manufacturing capabilities and practices (e.g. processing time) and therefore these are easier to understand and influence.

2.3. Manufacturing capabilities and practices in the context of energy and resource efficiency

Manufacturing capabilities and practices that enable or enhance environmental performance improvements have been widely explored in the literature [30, 31, 32]. It is possible to assume that companies that exhibit strong capabilities in certain areas of operations, could use these strengths to achieve their sustainability objectives. For example, in a case of metallic resource-intensive industries, authors argue that more advanced companies, in terms of sharing economy operations management practices, have mastered the capability of combining key principles of the circular economy and key elements of the sharing economy, creating an important synergy between the circular economy and the sharing economy [26].

By utilizing a practice maturity lens, researchers can visualize what capabilities can be more aligned and useful in achieving different types of outcomes for circularity and better environmental performance at product or process level [13, 14, 17]. It is also possible to link corporate maturity profiles with organizational behavior and strategies that enable a transition to better environmental performance [33, 34, 35]. Within the context of scalability of TF outputs, the authors argue that practice maturity at facility systems level are particularly important for easier adoption and integration of new technologies.

2.4. Assessment frameworks and models

Several researchers have contributed to the development of models and metrics for assessing circularity and evaluating the sustainability of products and services within the CE framework. Current circular economy models often lack a holistic perspective accounting for the complexities and interdependencies across value chains [36]. There appears to be

a need for consolidated tools that assess company readiness across dimensions like capabilities, resources, partnerships and culture while also identifying tailored pathways for implementation, evaluating trade-offs between economic and environmental viability, and determining critical success factors [10, 37]. Limitations remain in terms of comprehensive coverage, more precise eco-efficiency assessment, strategic guidance, and consideration of economic and environmental drivers for achieving a sustainable circular economy [38, 39, 40]. Relevant sustainability frameworks and methods in the literature remain mostly theoretical and therefore the opportunity to develop a framework that is informed by collaborative R&D project outputs is compelling and can be useful for funders, industry, and academics.

3. Framework design and data collection

As TF project research outputs are being generated on materials and process technologies, the case for scalability needs to be developed as well. By taking a more granular view on individual companies as opposed to a sector view, it is possible to gain a more pragmatic understanding around the techno-economic realities of adopting TF outputs. To develop a diagnostic framework that serves this purpose and make this useful for the foundation industries community, the authors followed the methodology guidelines from Maier et al. [41]. Similar frameworks in the sustainability context, use a combination of descriptive and prescriptive studies that allow developers to remain connected to the audience of the framework and its diagnostic nature [13, 14, 42].

3.1. Framework and tool structure

The conceptual assessment framework that can be derived from a conceptual synthesis of literature findings. To better understand the potential for scalability a set of assessments are combined:

- a) product strategy assessment in the context of circular economy based on the maturity model by Saidani et al, which in turn is using Stahel's concepts on circularity flows [15, 43]
- b) capability and practice maturity assessment (1-5, 1: low practice maturity and low eco-efficiency performance and 5: high practice maturity and best-in-class eco-efficiency performance). This is used as a proxy for readiness of adoption and performance expectations at manufacturing facility level [44]
- c) economic drivers' assessment, indicating for example areas where public funding and industrial policies can be better utilized and developed (as per section 2.2)

The articles that have been referenced here have also been selected based on internal consistency and compatibility with each other. These articles follow the Design Research Methodology and incorporate maturity models (in (a) and (b) developed in line with Maier et al. [41, 45]. Two possible options can be used to evaluate the framework's usability and usefulness [41, 42]. The first is to run a set of diagnostics about one of the TF outputs with companies that may be able to adopt this output. For instance, there is no certainty that a new

material can be utilized by more than one companies, even if it seems feasible on a technical and scientific basis; thus the case for scale remains limited. The second option is to survey companies in the TF network about their product strategies, capabilities and economic drivers and map out the areas where public funding for research and development can be most impactful. Descriptive studies can then be followed by a prescriptive study that can provide more in depth information and verification to the outputs of the descriptive study as per Blessing and Chakrabarti [45]. In this current article, the authors cover usability aspects of this framework by running a descriptive study on “spent foundry sand”, a material that has been researched extensively in TF for utilization by ceramics companies [46]. The authors then continue to reflect on the qualities of this framework against a set of parameters defined for assessment tools for circular economy [42, 47].

3.2. Data collection for the descriptive study

One of the materials that can be utilised further by refractories is Spent Foundry Sand (SFS). Previous studies on the impact of SFS on materials performance lack comprehensive research, and the performance characterization in individual cases is partial or lacks comprehensive testing. Current studies on SFS reuse are mostly concentrated on independent case studies. For example, Aggarwal et al., concluded that SFS can be used as 100% substitute of the conventional constituents (cement and natural sand) for the development of excavatable controlled low strength materials suitable for general backfill and utility trench backfill purposes [48]. Myrmin et al found that utilising SFS and other waste materials as new input raw materials to produce sustainable ceramics with high chemical, mechanical, and physical properties could reduce environmental pollution [49]. However, there is a lack of multi-faceted comprehensive analysis that combines technology, economics, and the environment [46].

Taking SFS as one example of TF outputs for possible utilization from two refractories companies (both making bricks for construction as primary product family), the authors present the use of the framework developed here and key findings from the application in this descriptive phase of the framework development.

Both companies are anonymous in this study, due to confidentiality constraints. Information on economics and organizational capabilities was sought through semi-structured interviews with 2 technical experts in two companies. The expert in company A was a TF academic that had been seconded to one of the partnering companies for a period of 3 months. The interviews practically followed the structure of the framework and respondents offered their views on the lists presented in table 1. In addition, the results (Table 1) were presented to UKRI funders during a review meeting to demonstrate the logic of the framework and constructs. Following a positive reception of this conceptual framework, the authors currently design the next stage of data collection through a prescriptive study.

4. Descriptive study results

Two companies that make bricks were presented with the option to use SFS in their product mix with a view to offset the use of raw materials at a lower price. Company A is a leading international provider of building materials and infrastructure solutions. The company specializes in production of bricks, primarily for wall construction, facades, and paving. It also has a significant presence in the production of clay roof tiles. The company's products are recognized for their superior quality, durability, and aesthetic appeal. Committed to a sustainable and energy-efficient construction sector, the company continually invests in innovative solutions to meet these objectives. Company B is a small-scale (50,000 bricks p.a.) ceramics industry located in India and the assessment was focused on the use of 50% w/w SFS to manufacture Class 3 bricks, typically used for single-story houses.

Table 1. Assessment of SFS as an option for Companies A and B

	Company A	Company B
<i>A. Product strategies for CE</i>		
• Narrowing		
- Lightweight Design	-	X
- Standardization	X	X
• Regenerative		
- Non-toxic materials	X	-
• Slowing		
- Physical durability	-	X
<i>B. Maturity grid dimensions (1-5)</i>		
• Energy mgt	2	2
• Resource mgt	4	3
• Waste mgt	4	2
• Supply chain mgt	2	3
<i>C. Economic drivers</i>		
• transportation costs	-	X
• access to new markets	X	X
• product quality	X	X
• processing time	X	-

For brevity in this article, only key highlights are presented in Table 1 for illustration of the intended use to the reader (as opposed to lengthy checklists). Using this assessment framework allowed the authors to visualize the areas where differences and similarities exist between companies, understand how long it takes to communicate the framework and its purpose to its audience and identify corrections that can be applied before wider application within TF.

5. Framework evaluation

In order to assess the usability of this framework in line with the circularity context and design research methodology, the evaluation points by Blomsma et al., are utilized and results are presented in Table 2 [42]. This evaluation was conducted by the authors, who are all actively involved in TF and collaborate with partnering companies.

Table 2. Framework evaluation as per Blomsma et al., (2019) assessment points

Criteria	Current framework (Low-Medium-High)
a) A tool for inspiring, motivating and aligning people.	L-M
b) Balance the generation of new ideas, with that of describing existing situation.	H
c) Provide an overview of the spectrum of available strategies ranging from incremental to transformative.	H
d) Indicate which strategies affect which business processes and related capabilities	H
e) Explicitly include the reduction and avoidance of resource use and impacts, as well as resource productivity strategies aimed at continued use and value delivery.	L-M
f) Allow for generating insight into circular configurations	L-M

The evaluation points used offer a structured approach for authors to reflect on framework improvements in content as well as in terms of its application. For example, more development is required in offering users a more engaged experience and using this framework for alignment between different companies in foundation industries (point a). In addition, points (f) and (e) indicate that there would be more value for users if quantitative data are used during the application of the framework. For instance, this can be done by informing the framework with data from successful sustainability implementations and best practice examples.

Reflecting on some the strengths of the framework there is high probability that this framework can connect new ideas (like SFS) with existing situations in industry and help users understand which barriers need attention (for example market access enablers). There is also a possible connection that the framework is making between product development strategies and impacts on business processes and related capabilities. For example, introducing SFS to the existing product mix may change the toxicity risk profile of products and processes. This change would require advanced analytical chemistry and materials testing capabilities, which in the short term will only benefit organizations that already have these in-house.

6. Conclusions and next steps

The analysis of the two cases in possibly using SFS demonstrates that the framework developed could evolve into an analytical tool that helps researchers and policy makers to better understand the gaps and opportunities in technology transfer for foundation industries. The framework consists of three structural pillars (sub-assessments) that can help identify the areas where more development could take place for emerging solutions from research to become more widely adopted from industry. The rationale behind this framework is related to scalability of solutions that can be tailored and adopted by different companies, thus achieving sustainability results at scale. Initial signs of usability are demonstrated through the SFS study, indicating that the structural

components of the framework can explain some of the adoption challenges that the foundation industries face.

Some of the limitations of this study are related to the application of this framework (i.e. collecting more data from multiple companies in the same sector), the validity of the data collected (i.e. collecting data through a focus group or individual experts) and usefulness (i.e. how this framework enables better decisions at policy making for foundation industries). More development is also required to understand the interdependencies between the framework constructs. For example, how product development strategies are connected to varying maturity levels and economic drivers.

Acknowledgements

This article was possible thanks to funding from Engineering and Physical Sciences Research Council (project reference: EP/V054627/1).

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2024

Elsevier

<https://doi.org/10.1016/j.procir.2024.03.043>

Litos L, Paddea S, Salonitis K, Jolly M. (2024) A conceptual assessment framework for sustainability in the foundation industries. Procedia CIRP, Volume 128, 2024, pp. 692-697