Measuring Resource Efficiency and Resource Effectiveness in Manufacturing

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Measuring Resource Efficiency and Resource Effectiveness in Manufacturing

Abstract

Purpose: *To identify and analyse existing resource efficiency and resource effectiveness measures and indicators (REMIs); identify gaps and develop a new indicator of 'operational resource effectiveness' (ORE_{ft}) suitable for manufacturing units.*

Methodology: *Research methodology consist of 3 stages: gap Identification, development and testing. Through review of academic literature, 40 REMIs are identified and analysed. A survey of manufacturers is carried out to validate the hypothesis and seek inputs on the development of the new indicator. The proposed indicator is tested by comparing ORE_{ft} index of two manufacturing units with each other, with resource intensity per unit (RIPU), waste intensity per unit (WIPU) and with 4 other REMIs.*

Findings: *Analysis of 40 REMIs clearly points towards the absence of a hypothesised REMI. 78% of manufacturers surveyed in north England substantiate the hypothesis. Inverse correlation established between the proposed ORE_{ft} indicator, RIPU, WIPU and other comparisons is likely to validate the output generated by the proposed indicator.*

Research Limitations: *Testing of this indicator is limited to two dissimilar manufacturing units that shared data.*

Practical Implications: *The proposed indicator is useful for comparing the operational resource effectiveness of individual factories over a period as well as with other factories. RIPU and WIPU captured in this indicator also represent operational resource efficiency that can be used to initiate improvement action.*

Originality: *Inclusion of both, the resource consumption and the waste generation along with discount/multiplying factors that capture the circularity aspects is likely to be the distinguishing feature of this indicator.*

Keywords: *Manufacturing, Resource Efficiency, Resource Effectiveness, Sustainability, Performance Measures*

Paper Type: *Research paper*

1. Introduction:

"Humankind has consumed more aluminium, copper, iron and steel, phosphate rock, diamonds, sulphur, coal, oil, natural gas, and even sand and gravel over the past century than over all earlier centuries put together, and the pace continues to accelerate" (Tilton, 2003). With rapidly increasing consumption of energy and material resources in the developed as well as the developing world, the issue of resource scarcity is becoming vital. The resource efficiency (RE) programme by United Nations Environment Programme (UNEP) emphasise that to meet the needs of the growing population, it is necessary to "decouple resource use and environmental degradation from the economic growth". This will necessitate consumers in making social and environmental concerns, part of their buying decisions. It will require producers to change their design, production and marketing processes (UNEP, 2014). Duflou et al. (2012) argue that while the manufacturing sector plays a vital role in the world economy, it consumes significant amounts of energy and other natural resources and releases solid, liquid, and gaseous wastes that lead to increased stress on the already fragile environment. Parker (2007) observe that unless new approaches to manufacturing are found and implemented, global population growth alone is expected to cause emissions and waste production to increase by at least 40% by 2050.

Measuring, monitoring and improving resource efficiency and/or resource effectiveness can be one of the approaches to addressing the issue of resource scarcity highlighted above. This research aims to identify and analyse some of the existing resource efficiency and resource effectiveness measures and indicators (REMIs); identify gaps and develop a 'new indicator' of 'operational resource effectiveness' (ORE_{ft}) suitable for manufacturing units.

2. Literature Review:

2.1. Resource efficiency and resource effectiveness:

Cambridge dictionary defines ‘efficiency’ as “good use of time and energy that does not waste any” and being ‘effective’ is defined as “successful or achieving the results you want”. Efficiency and effectiveness can be differentiated between how well something is done (efficient) and how useful something is (effective) (Diffen, 2015). In his book titled ‘The Effective Executive’, Peter Drucker aptly differentiates the two by stating that “efficiency is doing the thing right and effectiveness is doing the right thing”. Kao et al. (1995) argue that a conversion process normally involves many intricate activities, many inputs and many outputs that limit the level to which efficiency gains can be achieved. Fearne and Fowler (2006) observe that there is evidence to suggest that focus on ‘efficiency’ considerations undermines the need for delivering projects ‘effectively’ against the set objectives.

UNEP defines resource efficiency (RE) from the perspective of value chain and product life cycle as “reducing the total environmental impact of the production and consumption of goods and services, from raw material extraction to final use and disposal” (UNEP, 2010). In a policy document, Jansen (2013) highlights the fact that the current focus of RE of European Union Member States is restricted to improving the efficiency of use of input ‘natural resources’ such as fossil fuels, rare earth metals, and water. It further elaborates on the European Commission’s (EC) flagship initiative of ‘Resource Efficient Europe’ that defines resources to include all-natural resources that act as inputs to a nation’s economy. The EC captures the essence of RE by defining it as “A way to deliver more with less (natural resources)”. Similarly, the Australian Environment Protection Agency (EPA) defines RE as “doing more with less – creating more value with less impact” (EPA-Tasmania, 2013). The Australian EPA further describes RE in business terms as “process optimisation to limit consumption of energy, water and materials and output of waste products”. Although ‘resource efficiency’ policies cannot by themselves reduce exposure to sudden shortages or rise in prices, they can surely reduce their impacts. Shortages and sudden price rises on world market are quite often created by speculation, man-made and natural disasters, geopolitical crises or rising demand in a specific application. Economic resilience and ‘environmental sustainability’ can only be achieved with contributions from all members of the value chain across the globe working towards achieving RE. Otherwise, pressure on reducing resource consumption in only one economic block could see shifting of economic activities to less efficient parts of the world. This in turn is likely to increase pressure on Earth's bio capacity as a whole (Euromines, 2011).

In the context of 'environmental sustainability', there is no formal definition of 'resource effectiveness'. It could be defined as "To manage and optimise consumption of non-renewable and hazardous natural resources with an objective of achieving environmental sustainability". Management and optimisation could include complete elimination or reduction in the consumption of non-renewable natural resource(s) and/or replacement of non-renewable natural resource(s) with renewable natural resource(s). It could also include complete elimination or reduction in consumption of hazardous natural resources and/or replacement of hazardous natural resources with environmentally benign natural resources.

The strategic objective of 'environmental sustainability' cannot be achieved even with 100% resource efficiency at each stage of the supply chain. This is because non-renewable natural resources are finite. Therefore, to achieve the strategic objective of 'environmental sustainability', manufacturers may have to be 'resource efficient' as well as 'resource effective'. The 'circular economy' business model seems to be the desirable approach to doing things right (efficiently) as well as doing the right things (effectively). The 'circular business model' ensures not only recovery, reprocessing and reuse of waste streams but also replacement of non-renewable natural resources with renewable natural resources and replacement of hazardous resources with environmentally benign resources. Gharfalkar et al. (2015) capture the circularity aspect in the '5Rs of Resource Effectiveness' (Fig 2). In the context of manufacturing, it could be termed as 'Resource Effective Manufacturing' ($RE_{ft}M$). $RE_{ft}M$ could be defined as "Manufacturing environmentally benign products using nil or reduced quantity of non-renewable and hazardous natural resources that eliminates or reduces the generation of environmentally damaging waste streams".

2.2. Need for measuring resource efficiency or resource effectiveness:

Huysman et al. (2015) observe that the transition towards more resource efficient economies that is necessitated by challenges related to natural resources will need 'quantitative indicators' that are able to track consumption of 'natural resources' and the impacts associated with production and consumption systems. The European Commission (EC) highlights the importance of changing consumption patterns and improving products where consumers would buy products that last longer and/or products that could be easily reused or recycled. To achieve the objective of 'sustainable development', the EC's initiative on 'Resource Efficient Europe', emphasises the need for mandatory as well as voluntary 'measures of resource efficiency'. It highlights the need for developing robust and easily understandable 'indicators' that will provide signals and measure the progress of resource efficiency. The EC wants Member States to put in place incentives to motivate companies to "measure, benchmark and improve their resource efficiency systematically" (EC, 2011). Therefore, to improve resource efficiency and/or resource effectiveness, it is necessary to assess it using appropriate measures and/or indicators of resource efficiency or resource effectiveness (REMI). Gaussin et al. (2013) observe that as indices become more comprehensive, they get more complicated and often include large number of 'difficult-to-quantify' parameters such as societal impact.

2.3. Measures and Indicators of resource efficiency and effectiveness:

Oxford dictionary defines a "measure" as "to ascertain the size, amount or degree of (something) by using an instrument or device marked in standard unit" and defines an "indicator" as "a thing that indicates the state or level of something". Cambridge dictionary defines a "measure" as "to discover the exact size or amount of something" and defines an "indicator" as "something that shows what a situation is like". For example, while, the amount of solid waste generated can be considered as a "measure", solid waste generated per unit of production could be considered as an "indicator" that affects environmental sustainability.

This section deals with the identification of existing resource efficiency and resource effectiveness measures and/or indicators (REMIs). The literature search is conducted by identifying peer reviewed articles published in English language using the ‘Discovery’ database search engine. All fields (Titles, subject terms (key words) and abstracts) of literature in these databases are Boolean searched using the search phrases “Resource Efficiency Indicator” or “Resource Efficiency Index” “Resource Efficiency Measure” or “Resource Effectiveness Indicator” or “Resource Effectiveness Measure” or “Resource Effectiveness Index” for the period beginning 1987 to 2017. The publication of the Brundtland Commission report in 1987 made ‘sustainable development’ prominent for the first time. Therefore, the cut off year for literature search is set as 1987. Overall criteria for selection of relevant literature and the number of useful articles identified through this process are summarised in Table 1. Forty REMIs that are identified because of this search are summarised in Table 2.

Table 1: Summary of database search

Table 2: REMIs identified through literature survey

3. **Research Methodology**:

As depicted in Fig 1, the research methodology consists of three stages: i) gap identification, ii) development and iii) testing. The research is based on the foundation of two streams of investigation: literature survey and industry survey. Apart from identification of some of the existing REMIs, the literature survey aimed to understand the ‘resources’ that are relevant for achieving ‘environmental sustainability’ in manufacturing. It also aimed to understand the contextual background of measuring resource efficiency and/or resource effectiveness in achieving ‘environmentally sustainability’. Both these lines of investigation are used to identify gaps in some of the existing REMIs that are used for the development of *a “new indicator”*.

This research attempts to overcome some of the problems of complexity and assumptions by focusing on a few but important elements of ‘resource consumption’ and ‘waste generation’ for which operational data is easily available within a manufacturing unit (Fig 3). Scope of this research is limited to developing an aggregate indicator for measuring “operational resource effectiveness” (ORE_{ft}) of existing manufacturing units. The proposed indicator is based on the following hypothesis:

"An indication of resource effectiveness of a manufacturing unit can be obtained by combining 'input measures' that capture 'consumption of key natural resources' with 'output measures' that capture 'generation of waste', based on operational data that is easily available within the manufacturing unit".

Fig 1: Research methodology

3.1. Gap Identification:

This stage that has two strands of investigation involves identification of some of the existing REMIs and areas for improvement in the identified REMIs.

a. *Literature survey and*
b. *Industry survey*

Published literature is used to identify some of the existing REMIs. Identified REMIs are analysed using a set of qualitative and quantitative criteria. The quantitative criteria are summarised in Table 1. The second strand of investigation include a web-based survey of manufacturers in north England to understand if they use any REMIs. Both strands of investigation attempt to capture the REMIs that are in use and whether any of those REMIs capture both, 'resource use' and 'waste generation' in its measurement. It also attempts to understand whether the current measurements are based on operational data available within the manufacturing unit. The industry survey also assesses the level of data availability for various elements of the proposed 'Operational Resource Effectiveness' (ORE_{ft}) indicator identified in Fig 3. Findings are used in the development of the new indicator.

3.1.1. Criteria for analysis of identified REMIs:

Mostly qualitative analysis of REMIs has been undertaken. For example, Moffatt et al. (2001) assess a number of resource efficiency (RE) measures based on three sets of qualitative criteria such as robustness, practicality and usefulness to policy makers. Similarly, Hirschnitz-Garbers and Srebotnjak (2012) use a set of six qualitative criteria such as LCA compatibility, coverage of industries, sustainability impact coverage, policy relevance, required data efforts, and data availability. Each of these measures is qualitatively ranked as low, medium or high under each of the six key criteria.

In this research, qualitative as well as quantitative analysis of 40 identified REMIs is carried out. Points are allocated to different criterion under each of the three categories, whose scores are summarised in Table 3. Since all categories do not score equally, they are mean normalized for parity. Each of the three categories is further divided into individual criterion that is scored individually depending on its relevance and importance to 'environmental sustainability'.

Table 3: Categories of criteria used for the analysis of REMI

As the focus of this research is on developing an aggregate 'operational resource effectiveness' (ORE_{ft}) indicator suitable for manufacturing units, lower criterion scores for REMIs occur at global or national level (score = 0) than those that can measure resource efficiency (RE) for a product across its life cycle (score = 5). Examples of criterion scores for different boundary line suitability of REMIs are as given below:

- *REMI suitable for measuring RE at global and/or national level only = 0*
- *REMI suitable for measuring RE of individual factory (Gate2Gate) = 1*
- *REMI suitable for measuring RE of individual process (Gate2Gate) = 2*
- *REMI suitable for measuring RE of each product (Gate2Gate) = 3*
- *REMI suitable for measuring RE of product across supply chain (Cradle2Gate) = 4*
- *REMI suitable for measuring RE of product across life cycle (Cradle2Grave) = 5*

The 'resource consumption' related category (Table 3) scores more than the other two categories. This is because it deals with various aspects of 'resource consumption', which is the key element of environmental sustainability. Also, this category has the maximum number of subcategories in it. Each subcategory is further divided into number of individual criterions. For example, the subcategories include capturing of different types of energy (non-renewable, recovered, and renewable), materials (non-renewable, reused, reprocessed, and renewable), water (fresh and recovered) etc. The assessment criterion assigns higher scores for REMIs that separately capture and discount 'recovered' resources and maximum score for capturing and discounting 'renewable' resources. Examples of the individual criterion scores for different types of energy captured by each REMI in its calculation are as listed below:

- *REMI does not capture consumption of renewable energy = 0*
- *REMI aggregates consumption of renewable and non-renewable energy = 1*
- *REMI separately captures consumption of renewable and non-renewable energy = 2*
- *REMI discounts consumption of renewable energy = 3*

Also, since the aim is to develop an aggregate ORE_{ft} indicator that 'simultaneously' capture number of 'key elements of resource efficiency or resource effectiveness' in its calculation, higher scores are allocated to REMI that capture more 'key elements of resource efficiency or resource effectiveness' in its measurement. As hypothesised, 'consumption of key natural resources' and resultant 'waste generation' are considered as the 'key elements of resource efficiency or resource effectiveness' (Fig 3). Therefore, while most other criteria are scored on a band of 0 to 5 in increments of 1, a score of 0 or 5 is allocated to each of the 'key elements of resource efficiency or resource effectiveness'. These include key natural resources such as 'energy', 'materials', 'water' and 'land' use on the 'consumption side' and 'greenhouse gases', 'effluent' and 'solid waste' on the 'output side'. Individual criterion scores for these 'key elements of resource efficiency or resource effectiveness' are listed below. A REMI can score 5 in more than one 'key elements of resource efficiency or resource effectiveness' only if those 'key elements of resource efficiency or resource effectiveness' appear simultaneously in its calculation.

- *REMI captures Energy consumption in its measurement = 5*
- *REMI captures consumption of Materials in its measurement = 5*
- *REMI captures consumption of Water in its measurement = 5*

- *REMI captures Land use in its measurement = 5*
- *REMI captures generation of GHGs gases in its measurement = 5*
- *REMI captures generation of Effluent waste in its measurement = 5*
- *REMI captures generation of Solid waste in its measurement = 5*

3.1.2. Method used for industry survey:

A web-based survey is carried out with manufacturers in north England. The target audience include businesses from the manufacturing, engineering and processing industry, classified as "manufacturers" by the office of national statistics (ONS). FAME (Financial Analysis Made Easy) database is used to email manufacturers. 86 responses are received. The survey consists of total 44 questions but not all questions are applicable for all respondents. It is divided into 4 sections: 1 (consent form), 2 (about the respondent and his/her business), 3A (reasons for not measuring RE), 3B (how resource efficiency is measured in the organization) and 4 (inputs for the development of the new indicator). Sections 1,2 and 4 are applicable for all respondents.

3.2 Development Stage:

Based on the foundation of the hypothesis statement, this stage includes following aspects in the development of a conceptual framework and the algorithm for the new indicator of operational resource effectiveness (ORE_{ft}).

a. Seek inputs from the gaps identified from analysis of 40 REMIs and from the results of the survey of manufacturers in north England.
b. Identify elements or variables of the proposed ORE_{ft} indicator. This include decision on the resources and waste categories to be included in the proposed indicator. The 5Rs of resource effectiveness (Fig 2) and alternative hierarchy of resource use proposed by Gharfalkar et al. (2015) are also used in this decision making.
c. Introduction of circularity factors to differentiate various categories of resource use and waste generation. In absence of any academic research; policy guidelines or industry practices on circularity factors, ratios of Fibonacci

numbers are used for this purpose. Even if the ratios of integer numbers were used, the relative outcome would have been the same.

d. Decision on the units of measurement of each of the identified elements (variables) of the proposed indicator. To make the indicator unit free, all elements of the proposed ORE_{ft} indicator including production units are converted into the same unit of mass. For example, on the 'resource consumption' side, energy is converted into tons of oil equivalent, water and materials into tons. On the 'waste generation' side, Green House Gas (GHG) is converted into tons of carbon equivalent, effluent and solid wastes into tons.

3.2.1 *Theory behind the proposed ORE_{ft} indicator:*

As resource effectiveness, can be considered as one of the performance measures for achieving environmental sustainability, it is necessary to understand the philosophy of performance measurement. Neely et al. (1995) define performance as the efficiency and effectiveness of an action and performance measurement as the process of quantifying action. Stefan (2004) defines performance measure as a metric used to quantify the efficiency and/or effectiveness of an action that supports strategic objective. Bernolak (1997) observes that the data requirements should be limited to the necessary detail and frequency.

The concept of 'overall equipment effectiveness' (OEE) provided by Seiichi Nakajima is identified as suitable for developing the proposed ORE_{ft} indicator. While OEE is calculated by multiplying three different types of efficiencies: namely, availability, performance and quality, ORE_{ft} of a factory can be calculated by multiplying the efficiency or effectiveness of different elements of 'resource use' with the efficiency or effectiveness of different elements of 'waste generation' identified in Fig 3. The proposed indicator takes into consideration following underlying principles that are used for the development of the hypothesis statement:

a. Natural resources are scarce. Therefore, for achieving the strategic objective of 'environmental sustainability', the resource efficiency and/or resource effectiveness indicator should take into consideration consumption of key natural resources and ignore other resources such as time, money or manpower.

b. An indication need not be accurate and therefore it may not be necessary to capture all variables of environmental sustainability in its measurement. Therefore, the proposed indicator should capture only the most important variables of environmental sustainability (not all) such as energy, raw materials, water and waste.

c. Consumption of every natural resource has an impact, and a different impact, on the environment. Therefore, the indicator should not only capture the consumption of key natural resources but also the generation of waste.

d. Many of the existing REMIs are complex and dependent on data outside the organization and also on assumptions. Complex indicators are often not measured and monitored especially if they are dependent on data from multiple sources and/or if they are based on a set of assumptions. For adoption by the industry, measures or indicators must be based on readily available operational data rather than on assumptions.

3.2.2 Scope and system boundaries of proposed ORE_{ft} indicator:

For the purpose of this research, resources are grouped into two categories depending on their importance to 'environmental sustainability'. The first group is defined as 'primary resources' and includes the 'natural resources' that are primarily responsible for 'environmental sustainability'. The second group is defined as 'secondary resources' and comprise of 'natural' and 'human made resources' that play a secondary role in 'environmental sustainability'.

a. *Primary Resources:* Raw Materials, Consumables (Water), Energy (Oil; Gas; Coal…), Waste streams

b. *Secondary Resources*: Time, Human capital and Money capital

Since the strategic objective is to support "environmental sustainability", scope of the proposed indicator is limited to primary resources such as raw materials, water, energy and waste. It excludes secondary resources such as time, money (capital) or human capital.

On system boundaries, Huysman et al. (2015) observe that resource efficiency (RE) indicators have been developed for systems at micro-scale of specific processes and products to mesoscale and macro-scale of sectors and countries. At micro-scale, some indicators capture products and processes from factory entry gate to factory exit gate (Gate2Gate) while others consider full life cycle. Some indicators evaluate RE at regional or national level while others consider a more global perspective by including resources that are embodied in imported products.

The proposed indicator developed around the system boundary of a 'business unit' or a 'factory' is defined as the Gate2Gate ORE_{ft} indicator. It can measure 'operational resource effectiveness' for each 'business unit' or a 'factory' from its entry gate to exit gate (Gate2Gate). As in the case of the OEE, and as hypothesised, the scope of the proposed indicator is restricted to operational data. This aspect is substantiated by the industry survey (Fig 5). Also, an indicator that aims to be perfect by attempting to capture all aspects of environmental sustainability end up being too complex, lacks data availability and unless mandatory, is not accepted by the industry.

Table 4: System boundaries for mass balance (Jasch, 2002)

3.2.3 Elements of the proposed ORE_{ft} indicator:

The elements (variables) of the proposed indicator identified in Fig 3 are based on the circularity principles of the "5Rs of Resource Effectiveness" (Fig 2). To capture key elements of 'resource use' and 'waste generation', the framework considers the third 'R' that consists of 'recovery' options such as 'reuse' and 'reprocessing'. These 'recovery' options lead to the conversion of a 'waste' into a 'non-waste' (resource). The European waste directive 2008/98/EC, defines 'waste' as "any substance or object which the holder discards or intends to discard or is required to discard" (Directive, 2008). Elements of the proposed indicator takes into consideration the resource flows that could be measured in physical units of materials, energy and water flows as summarised in Table 4. To support the primary objective of 'environmental sustainability' only 'primary resources' categorised below are considered in the proposed indicator.

Virgin Resources:

a. Renewable virgin resources
b. Non-renewable virgin resources

Recovered Resources:

a. Reused (via repair, recondition, refurbish, remanufacture)
b. Reprocessed (upcycled, recycled, down-cycled)

Fig 2: 5Rs of Resource Effectiveness envisaged by (Gharfalkar et al., 2015)

Fig 3: Elements of proposed ORE$_{ft}$ indicator

3.2.4 Equations of the proposed Gate2Gate ORE$_{ft}$ indicator:

The concept behind 'Material Intensity per Unit Service' (MIPS or M1 in Table 2) is used for capturing each element of the proposed indicator identified in Fig 3. MIPS is calculated as mass of material input (MI) per total units of service (S) (Hinterberger and Schmidt-Bleek, 1999). Like MIPS, the proposed indicator captures consumption of different resources and generation of different wastes per unit of production in a factory. The proposed indicator is based on the resource flows that can be measured in physical units of materials, energy and water flow on the input side and flow of waste streams such as GHG, effluent, solid and hazardous waste on the output side (Fig 3). If product and/or process wise operational data for each element of the proposed ORE$_{ft}$ indicator identified in Fig 3 is available, then product and/or process wise ORE$_{ft}$ can be also assessed. But if it is not available, then all products manufactured in a factory need to be assigned the ORE$_{ft}$ of that factory.

Gate2Gate ORE$_{ft}$ = Resource Intensity per Unit x Waste Intensity per Unit

Gate2Gate ORE$_{ft}$ = RIPU x WIPU ……………………………………………………………… (1)

On the resource consumption side equations, following abbreviations are used:

RIPU: Resource Intensity per Unit

WIPU: Waste Intensity per Unit

EIPU: Energy Intensity per Unit

MIPU: Material Intensity per Unit

W_{tr}IPU: Water Intensity per Unit

RIPU = EIPU + MIPU + W_{tr}IPU …………………………………………………………………… (2)

Where,

EIPU = (Energy Consumption) / (Production Units) ……………….…………… (2a)

MIPU = (Material Consumption) / (Production Units) ………………………. (2b)

W_{tr}IPU = (Water Consumption) / (Production Units) ………………………… (2c)

Next level of elements of resource use as identified in Fig 3 are captured as below:

Energy = New Energy + Recovered Energy ……………………………….…….. (2a.1)

New Energy = Renewable Energy + Non-renewable Energy ……………...(2a.2)

As explained in the previous sections, consumption of only primary raw material (s) are considered in the consumption of materials.

Material = Virgin Material + Recovered Material

Virgin Material = Renewable Material + Non-renewable Material

Recovered Material = Reused Material + Reprocessed Material

Water Consumption = Fresh Water + Recovered Water

On the waste generation side equations, following abbreviations are used:

WIPU: Waste Intensity per Unit

GHGIPU: Greenhouse Gases Emissions Intensity per Unit

E_{ffl}IPU: Effluent Intensity per Unit

SWIPU: Solid Waste Intensity per Unit

E_{ffl}: Effluent

SW: Solid Waste

Haz: Hazardous

Nhaz: Non-hazardous

$WIPU = GHGIPU + SWIPU + E_{ffl}IPU$ ………………………………………………………………… (3)

Where,

$GHGIPU$ = (Quantity of Greenhouse gas generated) / (Production Units)... (3a)

$SWIPU$ = (Quantity of Solid Waste generated) / (Production Units) ………. (3b)

$E_{ffl}IPU$ = (Quantity of Effluent generated) / (Production Units) ……………… (3c)

The next level of elements of waste generation include hazardous and non-hazardous waste. They are further classified into waste that is sent for recovery and waste that is sent for disposal. Greenhouse gases (GHG) are hazardous and are invariably released to the atmosphere. Therefore, GHG are captured under hazardous waste and does not include the next level of recovery and/or disposal. Once the practice of carbon capture is well established, these levels may be added to the downstream equations of GHG.

GHG = Haz GHG ……………………………………………………………………………… (3a.1)

E_{ffl} = Haz E_{ffl} + Nhaz E_{ffl} ………………………………………………………………………. (3b.1)

Haz E_{ffl} = Haz E_{ffl} for recovery + Haz E_{ffl} for disposal ………………………… (3b.1.1)

Nhaz E_{ffl} = Nhaz E_{ffl} for recovery + Nhaz E_{ffl} for disposal …………………. (3b.1.2)

SW = Haz SW + Nhaz SW ………………………………………………………………. (3c.1)

Haz SW = Haz SW for recovery + Haz SW for disposal ……………………. (3c.1.1)

Nhaz SW = Nhaz SW for recovery + Nhaz SW for disposal ………….. (3c.1.2)

To encourage ‘circularity’, each element of ‘resource consumption’ are allocated a different ‘incentive’ or a ‘discount’ or a ‘multiplying’ factor called ‘circularity’ factor. For example, in the case of energy use, manufacturers need greater incentive to the use of renewable energy over recovered energy than over non-renewable energy. Similarly, in the case of materials, there must be more incentive for use of renewable materials over recovered materials over non-renewable materials. Within the recovered materials category, ‘reused’ materials are considered more resource efficient than ‘reprocessed’ (recycled, upcycled, down-cycled) materials. Same logic is applied for the use of fresh and recovered water. Since there is no precedence or research in the use of such 'circularity factor', the use of ratios of Fibonacci numbers starting with 1 for deriving the 'circularity factor' has been proposed. These factors are used in the detailed equations of the proposed Gate2Gate ORE_{ft} indicator to encourage circularity / environmental sustainability ($\alpha = 1/1$, $\beta = 1/2$, $Y = 1/3$, $\lambda = 1/5$).

'Circularity factors' are based on the hierarchy between different recovery options as proposed in the 'Hierarchy of Resource Use" by (Gharfalkar et al., 2015). Reuse could take place via repair and reuse, recondition and reuse, refurbish and reuse, remanufacture and reuse or any other operation and reuse. Reprocessing could include either recycling, upcycling or down cycling. Further, the hierarchy between various reuse options is based on the 'Hierarchy of Reuse Options" as proposed by (Gharfalkar et al., 2016).

Circularity factors for energy use:

The circularity factors for energy are based on the hierarchy of energy use where renewable energy is at the top, recovered energy at the middle and non-renewable energy at the bottom of the hierarchy.

Circularity factor for non-renewable Energy:

$\alpha = 1/1 = 1$ -> no discount as it does not support environmental sustainability

Circularity factor for recovered Energy:

$\beta = 1/2 = 0.5$ -> medium discount for encouraging circularity

Circularity factor for renewable Energy:

$Y = 1/3 = 0.33$ -> maximum discount for supporting environmental sustainability

Circularity factor for material use:

The circularity factors for material use are based on the hierarchy of material use where renewable materials are at the top, followed by reused materials (repaired/reconditioned/refurbished/remanufactured), reprocessed materials (recycled/upcycled/downcycled) and non-renewable materials at the bottom of the hierarchy in the same order.

Circularity factor for non-renewable materials:

α = 1 -> no discount as it does not support environmental sustainability

Circularity factor for reprocessed materials:

β= 1/2 = 0.50 -> it is less resource efficient than reused

Circularity factor for reused materials:

Y = 1/3 = 0.33 -> More resource efficient than reprocessed

Circularity factor for renewable materials:

λ = 1/5 = 0.20 -> maximum discount for supporting environmental sustainability

Circularity factors for water use:

The circularity factors for water use are based on the hierarchy of water use where recovered water is at the top and fresh water the bottom of the hierarchy.

Circularity factor for fresh water: α = 1 -> No discount

Circularity factor for recovered water: β = 1/2 = 0.5 -> Maximum discount

With above inputs of circularity factors, the equations for energy, material and water consumption are as mentioned below:

Energy Consumption = α (Non-renewable) + β (Recovered) + Y (Renewable)

= (Non-renewable) + 0.5 (Recovered) + 0.33 (Renewable)

Material Consumption = α (Non-renewable) + β (Reprocessed) + Y (Reused) + λ (Renewable) = (Non-renewable) + 0.5 (Reprocessed) + 0.33 (Reused) + 0.20 (Renewable)

Water Consumption = α (Fresh) + β (Recovered) = (Fresh) + 0.5 (Recovered)

Circularity factors for waste generation:

The circularity factors for waste generation are based on the hierarchy of waste where non-hazardous waste for recovery is at the top, followed by non-hazardous waste for disposal, hazardous waste for disposal and hazardous waste for recovery at the bottom of the hierarchy in the same order. These circularity factors are used for differentiating between hazardous and non-hazardous waste at the primary level as well as waste going for recovery and waste going for disposal at the secondary level.

Circularity factors for Hazardous Waste:

For disposal: α = 1 -> No discount / incentive

For recovery: β= 1/2 = 0.50

Circularity factors for Non-Hazardous Waste:

For disposal: Y = 1/3 = 0.33

For recovery: λ = 1/5 = 0.20 -> maximum discount / incentive

The final equation for the Gate2Gate ORE$_{ft}$ after consideration of circularity factor is as mentioned in equation number (4) and (5).

Gate2Gate ORE$_{ft}$ = RIPU after circularity x WIPU after circularity ……….. (4)

RIPU after circularity = EIPU after circularity + MIPU after circularity + W$_{tr}$IPU after circularity

WIPU after circularity = GHGIPU after circularity + E$_{ffl}$IPU after circularity + SWIPU after circularity

Gate2Gate ORE$_{ft}$ = ((Non-renewable energy) + 0.5 (Recovered energy) + 0.33 (Renewable energy) + (Non-renewable material) + 0.5 (Reprocessed material) + 0.33 (Reused material) + 0.20 (Renewable material) + (Fresh water) + 0.5 (Recovered water)) X ((GHG) + (Haz E$_{ffl}$ for disposal) + 0.5 (Haz E$_{ffl}$ for recovery) + 0.33 (Nhaz E$_{ffl}$ for disposal) + 0.2 (Nhaz E$_{ffl}$ for recovery) + (Haz SW for disposal) + 0.5 (Haz SW for recovery) + 0.33 (Nhaz SW for disposal) + 0.2 (Nhaz SW for recovery)) ………………………………………… (5)

Finally, the Gate2Gate ORE$_{ft}$ index of individual factory is derived as per equation (6). This equation ensures that the Gate2Gate ORE$_{ft}$ index can be measured on a scale of 0 to 1. It is assumed that higher the Gate2Gate ORE$_{ft}$ index score, better the manufacturing unit in terms of its resource effectiveness.

Gate2Gate ORE$_{ft}$ Index = 1 / (Gate2Gate ORE$_{ft}$)…………………………………………… (6)

3.3 Testing Stage:

Main objective of this stage is to test the validity of the proposed Gate2Gate ORE$_{ft}$ indicator. There are various definitions of validation. Oxford dictionary defines “to validate” as “to check or prove the validity or accuracy of”. Cambridge dictionary defines it as “to make something officially acceptable or approved, especially after examining it” and/or “to prove that something is correct”. Kirchner et al. (1996) defines ‘validity’ as the “adequacy for specific purpose”. Bockstaller and Girardin (2003) considers an indicator to be validated “if it is scientifically designed, if the information provided by it is relevant and if it is useful and used by the end users”.

General framework and methods for the validation of indicators at conceptual and output stage as suggested by Bockstaller and Girardin (2003) are summarised in Table 5. They clarify that the design or conceptual validation is important when the possibility of no other validation exist. Therefore, it is not necessary for a new indicator to be subjected to all types of validation.

a. *Conceptual validation*: To assess whether the indicator is scientifically founded.
b. *Output validation*: To assess the soundness of the outputs of the indicator.

Table 5: Framework for the validation of an indicator (Bockstaller and Girardin, 2003)

Following validation methods are adopted at the conceptual and output stage of the proposed Gate2Gate ORE$_{ft}$ indicator.

a. *Conceptual validation*: Review by experts' method is used for validating the concept of the proposed indicator. Manufactures are considered as the experts in this case and a web based "industry survey" is used to seek their inputs.

b. *Output validation:* Although 6 of the 86 manufacturers surveyed agreed to share data for testing of the indicator, only two shared their data: rubber products manufacturing unit and cast-iron foundry unit. The indicator is validated by establishing its relationship with consumption of resources per unit of production (RIPU) and generation of waste per unit of production (WIPU). The indicator is also validated by comparing the index with four other resource REMIs. It could not be compared with more REMIs due to lack of data as required for calculating other REMIs. Gate2Gate ORE_{ft} index of the two manufacturing units is also compared with each other to understand if and why one manufacturing unit is more resource effective than the other.

4. Results/Findings:

4.1. Findings of the analysis of 40 REMIs:

Outcome of the analysis of 40 REMIs using a set of quantitative and qualitative criteria is graphically depicted in Fig 4, Fig 5 and Fig 6. The graph in Fig 4 captures mean normalized scores of each of the 40 REMIs. These are further grouped into different blocks in two matrices as in Fig 5 & Fig 6. Proposed Gate2Gate ORE_{ft} indicator is also scored using the same set of criteria and plotted on the graph and the two matrices. In the 'Score versus Complexity Matrix' (Fig 5), the Y axis is grouped into three levels of scores: low score of 0 to less than 1, medium score between 1 to less than 2 and high score between 2 to 3. In the 'Data Availability versus Complexity Matrix' (Fig 6), the Y axis is grouped into three levels of data availability: low, medium and high. 'Low' indicates that a REMI is based on 100% assumptions; 'medium' indicates that it is based on a combination of operational data and assumptions, while 'high' indicates that it is based on 100% operational data. For both the matrices, the X axis is grouped into three levels of complexity: low, medium and high.

The analysis confirms that 75% of REMIs score below 1 against the mean normalised maximum possible score of 3 and the remaining 25% score between 1 to less than 2. Although, only two out of the 40 REMIs (M5 and M6) cross the half way mean normalized score of 1.5 (Fig 4), both, M5 and M6 are complex and not based on 100% operational data (Fig 5). Thirteen of the 40 REMIs (M2, M3, M12A, M12B, M14, M15, M16, M20, M21, M23, M24, M27 and M28) are low on complexity and high on data availability, but none of them simultaneously capture resource use and waste generation in their measurement (Fig 5; Fig 6 and Table 6).

Table 6: REMI grouping based on the aspects it captures in its measurement

Fig 4: Mean normalized scores of 40 REMIs and the proposed OREft indicator

Fig 5: Score versus Complexity Matrix

Fig 6: Data Availability vs Complexity Matrix

The three REMIs (M5, M6 & M15) that simultaneously capture both, resource consumption and waste generation in its measurements (Table 6) are high on complexity and not 100% based on easily available operational data. For example,

I. M5 (Ecological Footprint – Compound) relates to a country's use of resources to its land base. It involves estimation of net average per capita consumption of about fifty biotic resources, estimation of per capita land appropriated to produce each good or service and estimation of average annual per capita energy consumption for over hundred categories of traded goods. This is further converted to the amount of forested land necessary to sequester the emitted CO_2. Finally, the total ecological footprint is estimated by adding all the appropriated land areas. This is very complex, data intensive and low on data availability. Also, M5A is suitable for assessing resource efficiency only at national level.

II. M6 (Ecological Footprint – Component) is suitable for calculating footprint values for individual activities or components at local and personal level. But it is also complex, data intensive and low on data availability for all the 24 components that it takes into consideration in its measurement.

III. M15 (EMC) involves combining data from economy-wide material flow accounts such as direct material consumption (DMC) with data from life cycle analysis (LCA) by multiplying the mass of selected base materials with the LCA impact coefficients. Thirteen different impact categories of LCA are aggregated into one score by weighting. M13 is complex and not good on data availability.

IV. Although M13, M14, M16, M17, M18, M22, M23 and M30 are high on data availability and low on complexity, all of them are low on score.

V. Finally, while M34, M35, M36 and M37 are high on data availability and medium on complexity, none of them capture both, the resource use as well as waste generation in its measurement.

VI. None of the 40 REMIs provide incentives to encourage circularity in recovery, reprocessing or reuse of waste resources. With this major gap identified in the analysed REMIs, incentive/multiplying factor defined as circularity factors are used in the development of the proposed indicator.

VII. Analysis of 40 REMIs confirm that a REMI as per the hypothesis statement does not exist.

4.2. Results of the industry survey:

Key findings summarised here relate to the 86 responses by manufacturing, engineering and processing businesses in north England. These respondents are hereafter being called as “manufacturers”. Statistically, 86 responses represent the overall population of manufacturers in England at 94.1% expected incidence rate with +/- 5% error and 95% confidence level. The use of 90% Confidence levels with a margin of error of +/- 5% is considered reasonable for most audits / surveys (Bristol, 2015). Calculations of whether 86 responses represent the overall population of manufacturers in England are based on the sample size calculation mentioned below (Bristol, 2015):

$n = [c^2 \times N \times p \times (1-p)] / [(A^2 \times N) + (c^2 \times p \times (1-p)]$

Where,

n = sample size required

N = is the whole target population in question

p = is the average proportion of records expected to meet the various criteria

(1-p) is the average proportion of records not expected to meet the criteria

A = margin of error deemed to be acceptable (e.g. for 5% error either way, A = 0.05)

c = is a mathematical constant defined by the Confidence interval chosen (how sure we need to be of the result)

To be 95% sure of the result the constant c = 1.96

To be 90% sure of the result the constant c = 1.645

To be 80% sure of the result the constant c = 1.28

Three key findings of the industry survey are summarised below.

- 78% of manufacturers surveyed in north England agree that a good "resource effectiveness" indicator should include both, consumption of key natural resources and waste generation in its measurement (Fig 7).
- 54% of manufacturers surveyed in north England either strongly agree (16%) or agree (38%) that a good "resource effectiveness" indicator should be based on 100% operational data (Fig 8).
- Both the above findings substantiate the hypothesis statement.
- Considering current availability of data, 51% of manufacturers surveyed in north England recommend a system boundary of Factory Gate2Gate for the new indicator. Only 6% recommend a system boundary of Cradle2Gate for each product and 8% recommend a system boundary of Cradle2Grave for each product (Fig 9). This input is used to define the system boundary of the proposed resource effectiveness indicator as Factory Gate2Gate.

Fig 7: Elements of a good resource effectiveness indicator

Fig 8: Good resource effectiveness indicator should be based on 100% operational data

Fig 9: Preferred system boundary for a good resource effectiveness indicator

4.3. Results of case studies:

4.3.1. Gate2Gate ORE_{ft} index vs RIPU and WIPU:

Correlation between the resource intensity per unit (RIPU), waste intensity per unit (WIPU) and Gate2Gate ORE_{ft} index of the rubber products manufacturing and foundry unit is analysed. For both the units, it is observed that the Gate2Gate ORE_{ft} index is inversely proportional to RIPU as well as inversely proportional to WIPU of that manufacturing unit (Fig 10, 11, 12 and 13).

Fig 10: Rubber Unit: Resource Intensity Per Unit (RIPU) vs Gate2Gate ORE_{ft} Index

Fig 11: Rubber Unit: Waste Intensity Per Unit (WIPU) vs Gate2Gate ORE_{ft} Index

Fig 12: Foundry: Resource Intensity Per Unit (RIPU) vs Gate2Gate ORE_{ft} Index

Fig 13: Foundry: Waste Intensity Per Unit (WIPU) vs Gate2Gate ORE_{ft} Index

4.3.2 Comparison of Gate2Gate ORE_{ft} index of two manufacturing units:

Although it is not advisable to compare resource efficiency of two diverse manufacturing units such as a rubber product manufacturing and a foundry unit, a comparison of their Gate2Gate ORE_{ft} indices is carried out for academic purpose. It is assumed that the two units manufacture similar products. For a manufacturing unit to be resource efficient/productive than the other, it is necessary to have lower values of resource intensity per unit (RIPU) and/or waste intensity per unit (WIPU) vis-à-vis the other unit. RIPU is consumption of resources per unit of production and WIPU is generation of waste per unit of production. With this logic, the comparison of Gate2Gate ORE_{ft} index for these two units during 2013, 2014 and 2015 indicate that the first unit (in this case the rubber products manufacturing unit) is more resource efficient/productive than the second unit (foundry) in each year (Fig 14). Reasons why the first unit has a better Gate2Gate ORE$_{ft}$ index and therefore could be considered more resource efficient/productive than the second unit are mentioned below:

- 3 years' average consumption of resources per unit of production (RIPU) of the first unit is 6.00, which is 17% lower than that of the second unit whose average RIPU is 7.19 (Table 7).
- 3 years' average generation of wastes per unit of production (WIPU) of the first unit is 1.77, which is 22% lower than that of the WIPU of the second unit, which is 2.27 (Table 7).
- This means on an average; the first unit consume less resources per unit of production and generates lower waste per unit of production as compared to the second unit. Therefore, it may be inferred that the first unit is more resource efficient/productive than the second unit.

Table 7: RIPU, WIPU & Gate2Gate ORE$_{ft}$ Index of Rubber & Foundry Unit

Fig 14: Gate2Gate ORE$_{ft}$ index of Rubber Unit vs Foundry Unit

4.3.3 Comparison of Gate2Gate ORE$_{ft}$ index with other REMIs:

For validation/testing purpose, Gate2Gate ORE$_{ft}$ indices of the two manufacturing units are also compared with four REMIs described below:

a. *Resource productivity (M12A)*: Calculated as the monetary output per unit of all resources aggregated together. Since the two manufacturing units did not share monetary data, monetary output Is replaced with tons of production output. This Is divided by the aggregate of energy, material and water resources converted into equivalent tons.

b. *Material productivity (M20)*: Calculated as monetary output per unit of direct material consumed. Monetary output is replaced with tons of production output.

c. *Total material consumption (M21)*: It measures the total amount of materials directly used by a nation or a company or a business unit.

d. *Water productivity (M23)*: Calculated as monetary output per unit of fresh water consumed. Monetary output was replaced with tons of production output.

Values of the Gate2Gate ORE_{ft} index and the four REMIs for the foundry unit are summarised in table 8. Comparison of the Gate2Gate ORE_{ft} index with resource productivity (Fig 15), material productivity (Fig 16) and water productivity (Fig 17) shows similar trend between the compared indicators for 2012 to 2015. This is in line with the expectation that lower the resource/material/water productivity, lower the resource efficiency and vice-versa. Comparison of the Gate2Gate ORE_{ft} index with total material consumption shows an opposite trend (Fig 18). This is also in line with the expectation that lower the material consumption, higher the resource efficiency. Similar trends are observed for the plastic unit.

Table 8: Foundry unit: Gate2Gate ORE_{ft} Index vs REMIs

Fig 15: Foundry unit: Gate2Gate ORE_{ft} Index vs Resource Productivity M12A

Fig 16: Foundry unit: Gate2Gate ORE_{ft} Index vs Material Productivity M20

Fig 17: Foundry unit: Gate2Gate ORE_{ft} Index vs Water productivity M23

Fig 18: Foundry unit: Gate2Gate ORE_{ft} Index vs Total Material Consumption M21

5. Conclusions:

To summarize, none of the 40 analysed REMIs that were identified through the literature survey, capture both, the ‘resource use’, and ‘waste generation’ using 100% operational data in its measurement. Also, none of these REMIs provide incentives to encourage circularity in recovery, reprocessing or reuse of waste. 78% of surveyed manufacturers agreed that a good ‘resource effectiveness’ indicator should include both, consumption of key natural resources and waste generation in its measurement. Also, 54% of the manufacturers agree that a good ‘resource effectiveness' indicator should be based on operational data. Both these responses clearly validate the hypothesis. Finally, the inverse correlation established between the Gate2Gate ORE$_{ft}$ index and the RIPU and the WIPU of a foundry and plastic products manufacturing unit, comparison of the Gate2Gate ORE$_{ft}$ indices of these two units with each other and with four existing REMIs, validates the output generated by the new ORE$_{ft}$ indicator.

~~*Originality:*~~ The ORE$_{ft}$ indicator is a "new indicator" of "operational resource effectiveness" suitable for manufacturing units. Unlike many REMIs, the new ORE$_{ft}$ indicator is based on readily available operational data, not assumptions. In addition to the fact that the proposed indicator captures "resource consumption" and "waste generation" in its measurement, inclusion of "circularity factors" that capture the circularity of resource use and recovery and reuse of waste streams is ~~–~~the key distinguishing feature of this indicator.

~~*Practical Implications:*~~ ~~T~~in terms of its practical implications, the proposed indicator can be used for comparing the operational resource effectiveness of individual factories over a period as well as with other manufacturing units. It also captures useful information such as resource intensity per unit and waste intensity per unit, which also reflect operational resource efficiency or resource productivity that can be used to initiate improvement action. Adoption of this indicator across manufacturing supply chain can lead to an overall improvement in the resource efficiency, resource productivity, as well as resource effectiveness across the supply chain.

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~~*Limitations of research:*~~ ~~T~~ As far as the limitations of this research and the Gate2Gate ORE$_{ft}$ indicator are concerned, testing of this indicator ~~is~~was limited to two dissimilar manufacturing units that shared data. The validation could have been more effective if more units manufacturing similar products had shared their operational data. Also, lack of availability of data for any supply chain, restricted the testing of this indicator to Gate2Gate boundary of each manufacturing unit.

~~*Limitations of Gate2Gate ORE$_{ft}$ indicator:*~~ For a unit manufacturing a variety of products within the same campus, unless product or process wise resource

Formatted: Space Before: 6 pt, After: 6 pt consumption and waste generation data is available, this indicator cannot evaluate the resource effectiveness of individual products or processes within that campus. All products or processes within a campus are allocated the same resource effectiveness as that of the manufacturing unit. Also, the indicator considers consumption of only the primary raw materials. It does not differentiate between different raw materials as they are aggregated together by weight.

~~*Future Research:*~~ ~~A~~ Suggestions for future investigations include, conducting an industry survey ~~may be carried out~~ in other regions of the United Kingdom and/or Europe to create a database of Gate2Gate ORE_{ft} indices of similar and dissimilar manufacturing units. Further investigations~~research~~ may also be carried out targeting specific industrial segments such as the foundry or the plastic injection moulding units. This may help in identifying units with high Gate2Gate ORE_{ft} index, whose best practices could then be shared within the industry segment for overall improvement of that segment.

The linear system of 'make-use-dispose' is not environmentally sustainable. To achieve real long-term environmental sustainability, evolution of 'closed loop resource effective business models' is inevitable. These business models are likely to have renewable natural resources as inputs and outputs that are environmentally benign. This goal of environmental sustainability can be achieved if resource effectiveness is assessed at each stage of a product life cycle. Manufacturing is just one stage of this cycle. It may not be important how accurate or precise an indicator is but whether it gives some indication of resource effectiveness that could be used for initiating improvement actions. The proposed ORE_{ft} indicator is a new indicator that could be used by manufacturers for achieving this objective.

References:

ABDUL RASHID, S. H., EVANS, S. & LONGHURST, P. 2008. A comparison of four sustainable manufacturing strategies. *International Journal of Sustainable Engineering,* 1**,** 214-229.

BERNOLAK, I. 1997. Effective measurement and successful elements of company productivity: The basis of competitiveness and world prosperity. *International Journal of Production Economics,* 52**,** 203-213.

BOCKSTALLER, C. & GIRARDIN, P. 2003. How to validate environmental indicators. *Agricultural Systems,* 76**,** 639-653.

BRISTOL. 2015. *Sample Size Calculator* [Online]. Bristol University. Available: www.uhbristol.nhs.uk/files/nhs-ubht/sample_size_calculator.xls [Accessed 2015].

BURRITT, R. L. & SAKA, C. 2006. Environmental management accounting applications and eco-efficiency: case studies from Japan. *Journal of Cleaner Production,* 14**,** 1262-1275.

DALY, H. E. 1996. Operationalizing Sustainable Development by Investing in Natural Capital. *Beyond Growth: The Economics of Sustainable Development.* Boston: Beacon Press Books.

DIFFEN. 2015. *Effectiveness vs. Efficiency* [Online]. Seattle: Diffen. Available: http://www.diffen.com/difference/Effectiveness_vs_Efficiency [Accessed 10.01.2015 2015].

DIRECTIVE 2008. Directive 2008/98/EC of The European Parliament And of The Council on Waste and Repealing Certain Directives. Official Journal of the European Union.

DUFLOU, J. R., SUTHERLAND, J. W., DORNFELD, D., HERRMANN, C., JESWIET, J., KARA, S., HAUSCHILD, M. & KELLENS, K. 2012. Towards energy and resource efficient manufacturing: A processes and systems approach. *CIRP Annals - Manufacturing Technology,* 61**,** 587-609.

EC 2011. Roadmap to a Resource Efficient Europe: Communication from The Commission To The European Parliament, The Council, The European Economic and Social Committee and The Committee of The Regions. *In:* COMMISSION, E. (ed.). Brussels: European Commission.

EPA-TASMANIA. 2013. *Resource Efficiency* [Online]. Environment Protection Agency - Tasmania, Australia. Available: http://epa.tas.gov.au/sustainability/resource-efficiency [Accessed 8th August 2014].

EUROMINES 2011. Position on Resource Efficiency. *In:* EUROMINES (ed.) www.euromines.org. European Association of Mining Industries Metal Ores & Industrial Minerals.

EUROSTAT 2013. Resource Efficiency Scoreboard: Thirty indicators to measure resource efficiency in the EU. 186/2013 ed.: Eurostat Press Office.

FEARNE, A. & FOWLER, N. 2006. Efficiency versus effectiveness in construction supply chains: the dangers of “lean” thinking in isolation. *Supply Chain Management,* 11**,** 283-287.

GAUSSIN, M., HU, G., ABOLGHASEM, S., BASU, S., SHANKAR, M. R. & BIDANDA, B. 2013. Assessing the environmental footprint of manufactured products: A survey of current literature. *International Journal of Production Economics,* 146**,** 515-523.

GHARFALKAR, M., ALI, Z. & HILLIER, G. 2016. Clarifying the disagreements on various reuse options: Repair, recondition, refurbish and remanufacture. *Waste Management & Research*.

GHARFALKAR, M., COURT, R., CAMPBELL, C., ALI, Z. & HILLIER, G. 2015. Analysis of waste hierarchy in the European waste directive 2008/98/EC. *Waste Management,* 39**,** 305-313.

HERNANDEZ, A. G. & CULLEN, J. M. 2016. Unlocking Plant-level Resource Efficiency Options: A Unified Exergy Measure. *Procedia CIRP,* 48**,** 122-127.

HINTERBERGER, F. & SCHMIDT-BLEEK, F. 1999. Dematerialization, MIPS and Factor 10 Physical sustainability indicators as a social device. *Ecological Economics,* 29**,** 53-56.

HIRSCHNITZ-GARBERS, M. & SREBOTNJAK, T. 2012. Ecologic Policy Briefs - Integrating Resource Efficiency, Greening of Industrial Production and Green Industries - Scoping of and recommendations for effective indicators. *In:* KRAEMER, R. A. &

MULLER-KRAENNER, S. (eds.). Germany: Ecologic Institute for International and European Environmental Policy.

HUYSMAN, S., SALA, S., MANCINI, L., ARDENTE, F., ALVARENGA, R. A. F., DE MEESTER, S., MATHIEUX, F. & DEWULF, J. 2015. Toward a systematized framework for resource efficiency indicators. *Resources, Conservation and Recycling,* 95**,** 68-76.

HUYSVELD, S., DE MEESTER, S., VAN LINDEN, V., MUYLLE, H., PEIREN, N., LAUWERS, L. & DEWULF, J. 2015. Cumulative Overall Resource Efficiency Assessment (COREA) for comparing bio-based products with their fossil-derived counterparts. *Resources, Conservation and Recycling,* 102**,** 113-127.

JANSEN, J. 2013. Resouce Efficiency: What does it mean and why is it relevant? - Policy Brief. Petten, The Netherlands: ECN Policy Studies.

JASCH, C. 2002. How to define corporate environmental costs. *In:* TUKKER, A. & TNO-STB, D., THE NETHERLANDS (eds.) *Environmental Management Accounting: Informational and Institutional Developments.* The Netherlands: Kluwer Academic Publishers.

KAO, C., CHEN, L.-H., WANG, T.-Y., KUO, S. & HORNG, S.-D. 1995. Productivity improvement: Efficiency approach vs effectiveness approach. *Omega,* 23**,** 197-204.

KIRCHNER, J. W., HOOPER, R. P., KENDALL, C., NEAL, C. & LEAVESLEY, G. 1996. Testing and validating environmental models. *Science of the Total Environment,* 183**,** 33-47.

KITAJIMA, T., SAWANISHI, H., TAGUCHI, M., TORIHARA, K., HONMA, O. & MISHIMA, N. 2015. A Proposal on a Resource Efficiency Index for EEE. *Procedia CIRP,* 26**,** 607-611.

MODI, S. B. & MISHRA, S. 2011. What drives financial performance–resource efficiency or resource slack? *Journal of Operations Management,* 29**,** 254-273.

MOFFATT, I., HANLEY, N., ALLEN, S. & FUNDINGSLAND, M. 2001. Sustainable Prosperity: Measuring Resource Efficiency.

NEELY, A., GREGORY, M. & PLATTS, K. 1995. **Performance measurement** system design: a literature review and research agenda. *International Journal of Operations & Production Management,* 15**,** 80-116.

PARKER, D. 2007. An Analysis of the Spectrum of Reuse - A Component of the Remanufacturing Pilot for Defra BREW Programme. United Kingdom: Oakdene Hollins Ltd.

SPUERK, S., DROBE, M. & LOTTERMOSER, B. G. 2017. Evaluating resource efficiency at major copper mines. *Minerals Engineering,* 107**,** 27-33.

STEFAN, T. 2004. Performance measurement: from philosophy to practice. *International Journal of Productivity and Performance Management,* 53**,** 726-737.

TILTON, J. E. 2003. Chapter 1: The Road Ahead. *On Borrowed Time? Assessing the Threat of Mineral Depletion.* Washington, DC: Resources for the Future.

UNEP 2010. Resource Efficiency - Fact Sheet. Paris: United Nations Environment Programme.

UNEP. 2014. *UNEP's Resource Efficiency Programme* [Online]. UNEP. Available: http://www.unep.org/resourceefficiency/Home/UNEPsResourceEfficiencyProgramme/tabid/55552/Default.aspx [Accessed 7th July 2014].

VALERO, A., VALERO, A. & CALVO, G. 2015. Using thermodynamics to improve the resource efficiency indicator GDP/DMC. *Resources, Conservation and Recycling,* 94**,** 110-117.

Measuring Resource Efficiency and Resource Effectiveness in Manufacturing

Abstract

Purpose*: To identify and analyse existing resource efficiency and resource effectiveness measures and indicators (REMIs); identify gaps and develop a new indicator of 'operational resource effectiveness' (ORE_{ft}) suitable for manufacturing units.*

Methodology: *Research methodology consist of 3 stages: gap Identification, development and testing. Through review of academic literature, 40 REMIs are identified and analysed. A survey of manufacturers is carried out to validate the hypothesis and seek inputs on the development of the new indicator. The proposed indicator is tested by comparing ORE_{ft} index of two manufacturing units with each other, with resource intensity per unit (RIPU), waste intensity per unit (WIPU) and with 4 other REMIs.*

Findings: *Analysis of 40 REMIs clearly points towards the absence of a hypothesised REMI. 78% of manufacturers surveyed in north England substantiate the hypothesis. Inverse correlation established between the proposed ORE_{ft} indicator, RIPU, WIPU and other comparisons is likely to validate the output generated by the proposed indicator.*

Research Limitations: *Testing of this indicator is limited to two dissimilar manufacturing units that shared data.*

Practical Implications: *The proposed indicator is useful for comparing the operational resource effectiveness of individual factories over a period as well as with other factories. RIPU and WIPU captured in this indicator also represent operational resource efficiency that can be used to initiate improvement action.*

Originality: *Inclusion of both, the resource consumption and the waste generation along with discount/multiplying factors that capture the circularity aspects is likely to be the distinguishing feature of this indicator.*

Keywords*: Manufacturing, Resource Efficiency, Resource Effectiveness, Sustainability, Performance Measures*

Paper Type: *Research paper*

1. Introduction:

“Humankind has consumed more aluminium, copper, iron and steel, phosphate rock, diamonds, sulphur, coal, oil, natural gas, and even sand and gravel over the past century than over all earlier centuries put together, and the pace continues to accelerate” (Tilton, 2003). With rapidly increasing consumption of energy and material resources in the developed as well as the developing world, the issue of resource scarcity is becoming vital. The resource efficiency (RE) programme by United Nations Environment Programme (UNEP) emphasise that to meet the needs of the growing population, it is necessary to “decouple resource use and environmental degradation from the economic growth”. This will necessitate consumers in making social and environmental concerns, part of their buying decisions. It will require producers to change their design, production and marketing processes (UNEP, 2014). Duflou et al. (2012) argue that while the manufacturing sector plays a vital role in the world economy, it consumes significant amounts of energy and other natural resources and releases solid, liquid, and gaseous wastes that lead to increased stress on the already fragile environment. Parker (2007) observe that unless new approaches to manufacturing are found and implemented, global population growth alone is expected to cause emissions and waste production to increase by at least 40% by 2050.

Measuring, monitoring and improving resource efficiency and/or resource effectiveness can be one of the approaches to addressing the issue of resource scarcity highlighted above. This research aims to identify and analyse some of the existing resource efficiency and resource effectiveness measures and indicators (REMIs); identify gaps and develop a ‘new indicator’ of ‘operational resource effectiveness’ (ORE_{ft}) suitable for manufacturing units.

2. Literature Review:

2.1. Resource efficiency and resource effectiveness:

Cambridge dictionary defines 'efficiency' as "good use of time and energy that does not waste any" and being 'effective' is defined as "successful or achieving the results you want". Efficiency and effectiveness can be differentiated between how well something is done (efficient) and how useful something is (effective) (Diffen, 2015). In his book titled 'The Effective Executive', Peter Drucker aptly differentiates the two by stating that "efficiency is doing the thing right and effectiveness is doing the right thing". Kao et al. (1995) argue that a conversion process normally involves many intricate activities, many inputs and many outputs that limit the level to which efficiency gains can be achieved. Fearne and Fowler (2006) observe that there is evidence to suggest that focus on 'efficiency' considerations undermines the need for delivering projects 'effectively' against the set objectives.

UNEP defines resource efficiency (RE) from the perspective of value chain and product life cycle as "reducing the total environmental impact of the production and consumption of goods and services, from raw material extraction to final use and disposal" (UNEP, 2010). In a policy document, Jansen (2013) highlights the fact that the current focus of RE of European Union Member States is restricted to improving the efficiency of use of input 'natural resources' such as fossil fuels, rare earth metals, and water. It further elaborates on the European Commission's (EC) flagship initiative of 'Resource Efficient Europe' that defines resources to include all-natural resources that act as inputs to a nation's economy. The EC captures the essence of RE by defining it as "A way to deliver more with less (natural resources)". Similarly, the Australian Environment Protection Agency (EPA) defines RE as "doing more with less – creating more value with less impact" (EPA-Tasmania, 2013). The Australian EPA further describes RE in business terms as "process optimisation to limit consumption of energy, water and materials and output of waste products". Although 'resource efficiency' policies cannot by themselves reduce exposure to sudden shortages or rise in prices, they can surely reduce their impacts. Shortages and sudden price rises on world market are quite often created by speculation, man-made and natural disasters, geopolitical crises or rising demand in a specific application. Economic resilience and 'environmental sustainability' can only be achieved with contributions from all members of the value chain across the globe working towards achieving RE. Otherwise, pressure on reducing resource consumption in only one economic block could see shifting of economic activities to less efficient parts of the world. This in turn is likely to increase pressure on Earth's bio capacity as a whole (Euromines, 2011).

In the context of 'environmental sustainability', there is no formal definition of 'resource effectiveness'. It could be defined as "To manage and optimise consumption of non-renewable and hazardous natural resources with an objective of achieving environmental sustainability". Management and optimisation could include complete elimination or reduction in the consumption of non-renewable natural resource(s) and/or replacement of non-renewable natural resource(s) with renewable natural resource(s). It could also include complete elimination or reduction in consumption of hazardous natural resources and/or replacement of hazardous natural resources with environmentally benign natural resources.

The strategic objective of 'environmental sustainability' cannot be achieved even with 100% resource efficiency at each stage of the supply chain. This is because non-renewable natural resources are finite. Therefore, to achieve the strategic objective of 'environmental sustainability', manufacturers may have to be 'resource efficient' as well as 'resource effective'. The 'circular economy' business model seems to be the desirable approach to doing things right (efficiently) as well as doing the right things (effectively). The 'circular business model' ensures not only recovery, reprocessing and reuse of waste streams but also replacement of non-renewable natural resources with renewable natural resources and replacement of hazardous resources with environmentally benign resources. Gharfalkar et al. (2015) capture the circularity aspect in the '5Rs of Resource Effectiveness' (Fig 2). In the context of manufacturing, it could be termed as 'Resource Effective Manufacturing' ($RE_{ft}M$). $RE_{ft}M$ could be defined as "Manufacturing environmentally benign products using nil or reduced quantity of non-renewable and hazardous natural resources that eliminates or reduces the generation of environmentally damaging waste streams".

2.2. Need for measuring resource efficiency or resource effectiveness:

Huysman et al. (2015) observe that the transition towards more resource efficient economies that is necessitated by challenges related to natural resources will need ‘quantitative indicators’ that are able to track consumption of ‘natural resources’ and the impacts associated with production and consumption systems. The European Commission (EC) highlights the importance of changing consumption patterns and improving products where consumers would buy products that last longer and/or products that could be easily reused or recycled. To achieve the objective of ‘sustainable development’, the EC’s initiative on ‘Resource Efficient Europe’, emphasises the need for mandatory as well as voluntary ‘measures of resource efficiency’. It highlights the need for developing robust and easily understandable ‘indicators’ that will provide signals and measure the progress of resource efficiency. The EC wants Member States to put in place incentives to motivate companies to “measure, benchmark and improve their resource efficiency systematically” (EC, 2011). Therefore, to improve resource efficiency and/or resource effectiveness, it is necessary to assess it using appropriate measures and/or indicators of resource efficiency or resource effectiveness (REMI). Gaussin et al. (2013) observe that as indices become more comprehensive, they get more complicated and often include large number of ‘difficult-to-quantify’ parameters such as societal impact.

2.3. Measures and Indicators of resource efficiency and effectiveness:

Oxford dictionary defines a “measure” as “to ascertain the size, amount or degree of (something) by using an instrument or device marked in standard unit” and defines an “indicator” as “a thing that indicates the state or level of something”. Cambridge dictionary defines a “measure” as “to discover the exact size or amount of something” and defines an “indicator” as “something that shows what a situation is like”. For example, while, the amount of solid waste generated can be considered as a “measure”, solid waste generated per unit of production could be considered as an “indicator” that affects environmental sustainability.

This section deals with the identification of existing resource efficiency and resource effectiveness measures and/or indicators (REMIs). The literature search is conducted by identifying peer reviewed articles published in English language using the 'Discovery' database search engine. All fields (Titles, subject terms (key words) and abstracts) of literature in these databases are Boolean searched using the search phrases "Resource Efficiency Indicator" or "Resource Efficiency Index" "Resource Efficiency Measure" or "Resource Effectiveness Indicator" or "Resource Effectiveness Measure" or "Resource Effectiveness Index" for the period beginning 1987 to 2017. The publication of the Brundtland Commission report in 1987 made 'sustainable development' prominent for the first time. Therefore, the cut off year for literature search is set as 1987. Overall criteria for selection of relevant literature and the number of useful articles identified through this process are summarised in Table 1. Forty REMIs that are identified because of this search are summarised in Table 2.

Table 1: Summary of database search

Table 2: REMIs identified through literature survey

3. Research Methodology:

As depicted in Fig 1, the research methodology consists of three stages: i) gap identification, ii) development and iii) testing. The research is based on the foundation of two streams of investigation: literature survey and industry survey. Apart from identification of some of the existing REMIs, the literature survey aimed to understand the 'resources' that are relevant for achieving 'environmental sustainability' in manufacturing. It also aimed to understand the contextual background of measuring resource efficiency and/or resource effectiveness in achieving 'environmentally sustainability'. Both these lines of investigation are used to identify gaps in some of the existing REMIs that are used for the development of *a "new indicator"*.

This research attempts to overcome some of the problems of complexity and assumptions by focusing on a few but important elements of 'resource consumption' and 'waste generation' for which operational data is easily available within a manufacturing unit (Fig 3). Scope of this research is limited to developing an aggregate indicator for measuring "operational resource effectiveness" (ORE_{ft}) of existing manufacturing units. The proposed indicator is based on the following hypothesis:

"An indication of resource effectiveness of a manufacturing unit can be obtained by combining 'input measures' that capture 'consumption of key natural resources' with 'output measures' that capture 'generation of waste', based on operational data that is easily available within the manufacturing unit".

Fig 1: Research methodology

3.1. Gap Identification:

This stage that has two strands of investigation involves identification of some of the existing REMIs and areas for improvement in the identified REMIs.

a. *Literature survey and*

b. *Industry survey*

Published literature is used to identify some of the existing REMIs. Identified REMIs are analysed using a set of qualitative and quantitative criteria. The quantitative criteria are summarised in Table 1. The second strand of investigation include a web-based survey of manufacturers in north England to understand if they use any REMIs. Both strands of investigation attempt to capture the REMIs that are in use and whether any of those REMIs capture both, 'resource use' and 'waste generation' in its measurement. It also attempts to understand whether the current measurements are based on operational data available within the manufacturing unit. The industry survey also assesses the level of data availability for various elements of the proposed 'Operational Resource Effectiveness' (ORE_{ft}) indicator identified in Fig 3. Findings are used in the development of the new indicator.

3.1.1. Criteria for analysis of identified REMIs:

Mostly qualitative analysis of REMIs has been undertaken. For example, Moffatt et al. (2001) assess a number of resource efficiency (RE) measures based on three sets of qualitative criteria such as robustness, practicality and usefulness to policy makers. Similarly, Hirschnitz-Garbers and Srebotnjak (2012) use a set of six qualitative criteria such as LCA compatibility, coverage of industries, sustainability impact coverage, policy relevance, required data efforts, and data availability. Each of these measures is qualitatively ranked as low, medium or high under each of the six key criteria.

In this research, qualitative as well as quantitative analysis of 40 identified REMIs is carried out. Points are allocated to different criterion under each of the three categories, whose scores are summarised in Table 3. Since all categories do not score equally, they are mean normalized for parity. Each of the three categories is further divided into individual criterion that is scored individually depending on its relevance and importance to 'environmental sustainability'.

Table 3: Categories of criteria used for the analysis of REMI

As the focus of this research is on developing an aggregate 'operational resource effectiveness' (ORE_{ft}) indicator suitable for manufacturing units, lower criterion scores for REMIs occur at global or national level (score = 0) than those that can measure resource efficiency (RE) for a product across its life cycle (score = 5). Examples of criterion scores for different boundary line suitability of REMIs are as given below:

- *REMI suitable for measuring RE at global and/or national level only = 0*
- *REMI suitable for measuring RE of individual factory (Gate2Gate) = 1*
- *REMI suitable for measuring RE of individual process (Gate2Gate) = 2*
- *REMI suitable for measuring RE of each product (Gate2Gate) = 3*
- *REMI suitable for measuring RE of product across supply chain (Cradle2Gate) = 4*
- *REMI suitable for measuring RE of product across life cycle (Cradle2Grave) = 5*

The 'resource consumption' related category (Table 3) scores more than the other two categories. This is because it deals with various aspects of 'resource consumption', which is the key element of environmental sustainability. Also, this category has the maximum number of subcategories in it. Each subcategory is further divided into number of individual criterions. For example, the subcategories include capturing of different types of energy (non-renewable, recovered, and renewable), materials (non-renewable, reused, reprocessed, and renewable), water (fresh and recovered) etc. The assessment criterion assigns higher scores for REMIs that separately capture and discount 'recovered' resources and maximum score for capturing and discounting 'renewable' resources. Examples of the individual criterion scores for different types of energy captured by each REMI in its calculation are as listed below:

- *REMI does not capture consumption of renewable energy = 0*
- *REMI aggregates consumption of renewable and non-renewable energy = 1*
- *REMI separately captures consumption of renewable and non-renewable energy = 2*
- *REMI discounts consumption of renewable energy = 3*

Also, since the aim is to develop an aggregate ORE$_{ft}$ indicator that 'simultaneously' capture number of 'key elements of resource efficiency or resource effectiveness' in its calculation, higher scores are allocated to REMI that capture more 'key elements of resource efficiency or resource effectiveness' in its measurement. As hypothesised, 'consumption of key natural resources' and resultant 'waste generation' are considered as the 'key elements of resource efficiency or resource effectiveness' (Fig 3). Therefore, while most other criteria are scored on a band of 0 to 5 in increments of 1, a score of 0 or 5 is allocated to each of the 'key elements of resource efficiency or resource effectiveness'. These include key natural resources such as 'energy', 'materials', 'water' and 'land' use on the 'consumption side' and 'greenhouse gases', 'effluent' and 'solid waste' on the 'output side'. Individual criterion scores for these 'key elements of resource efficiency or resource effectiveness' are listed below. A REMI can score 5 in more than one 'key elements of resource efficiency or resource effectiveness' only if those 'key elements of resource efficiency or resource effectiveness' appear simultaneously in its calculation.

- *REMI captures Energy consumption in its measurement = 5*
- *REMI captures consumption of Materials in its measurement = 5*
- *REMI captures consumption of Water in its measurement = 5*

- *REMI captures Land use in its measurement = 5*
- *REMI captures generation of GHGs gases in its measurement = 5*
- *REMI captures generation of Effluent waste in its measurement = 5*
- *REMI captures generation of Solid waste in its measurement = 5*

3.1.2. Method used for industry survey:

A web-based survey is carried out with manufacturers in north England. The target audience include businesses from the manufacturing, engineering and processing industry, classified as "manufacturers" by the office of national statistics (ONS). FAME (Financial Analysis Made Easy) database is used to email manufacturers. 86 responses are received. The survey consists of total 44 questions but not all questions are applicable for all respondents. It is divided into 4 sections: 1 (consent form), 2 (about the respondent and his/her business), 3A (reasons for not measuring RE), 3B (how resource efficiency is measured in the organization) and 4 (inputs for the development of the new indicator). Sections 1,2 and 4 are applicable for all respondents.

3.2 Development Stage:

Based on the foundation of the hypothesis statement, this stage includes following aspects in the development of a conceptual framework and the algorithm for the new indicator of operational resource effectiveness (ORE_{ft}).

a. Seek inputs from the gaps identified from analysis of 40 REMIs and from the results of the survey of manufacturers in north England.

b. Identify elements or variables of the proposed ORE_{ft} indicator. This include decision on the resources and waste categories to be included in the proposed indicator. The 5Rs of resource effectiveness (Fig 2) and alternative hierarchy of resource use proposed by Gharfalkar et al. (2015) are also used in this decision making.

c. Introduction of circularity factors to differentiate various categories of resource use and waste generation. In absence of any academic research; policy guidelines or industry practices on circularity factors, ratios of Fibonacci numbers are used for this purpose. Even if the ratios of integer numbers were used, the relative outcome would have been the same.

d. Decision on the units of measurement of each of the identified elements (variables) of the proposed indicator. To make the indicator unit free, all elements of the proposed ORE_{ft} indicator including production units are converted into the same unit of mass. For example, on the 'resource consumption' side, energy is converted into tons of oil equivalent, water and materials into tons. On the 'waste generation' side, Green House Gas (GHG) is converted into tons of carbon equivalent, effluent and solid wastes into tons.

3.2.1 Theory behind the proposed ORE_{ft} indicator:

As resource effectiveness, can be considered as one of the performance measures for achieving environmental sustainability, it is necessary to understand the philosophy of performance measurement. Neely et al. (1995) define performance as the efficiency and effectiveness of an action and performance measurement as the process of quantifying action. Stefan (2004) defines performance measure as a metric used to quantify the efficiency and/or effectiveness of an action that supports strategic objective. Bernolak (1997) observes that the data requirements should be limited to the necessary detail and frequency.

The concept of 'overall equipment effectiveness' (OEE) provided by Seiichi Nakajima is identified as suitable for developing the proposed ORE_{ft} indicator. While OEE is calculated by multiplying three different types of efficiencies: namely, availability, performance and quality, ORE_{ft} of a factory can be calculated by multiplying the efficiency or effectiveness of different elements of 'resource use' with the efficiency or effectiveness of different elements of 'waste generation' identified in Fig 3. The proposed indicator takes into consideration following underlying principles that are used for the development of the hypothesis statement:

a. Natural resources are scarce. Therefore, for achieving the strategic objective of 'environmental sustainability', the resource efficiency and/or resource effectiveness indicator should take into consideration consumption of key natural resources and ignore other resources such as time, money or manpower.

b. An indication need not be accurate and therefore it may not be necessary to capture all variables of environmental sustainability in its measurement. Therefore, the proposed indicator should capture only the most important variables of environmental sustainability (not all) such as energy, raw materials, water and waste.

c. Consumption of every natural resource has an impact, and a different impact, on the environment. Therefore, the indicator should not only capture the consumption of key natural resources but also the generation of waste.

d. Many of the existing REMIs are complex and dependent on data outside the organization and also on assumptions. Complex indicators are often not measured and monitored especially if they are dependent on data from multiple sources and/or if they are based on a set of assumptions. For adoption by the industry, measures or indicators must be based on readily available operational data rather than on assumptions.

3.2.2 Scope and system boundaries of proposed ORE$_{ft}$ indicator:

For the purpose of this research, resources are grouped into two categories depending on their importance to 'environmental sustainability'. The first group is defined as 'primary resources' and includes the 'natural resources' that are primarily responsible for 'environmental sustainability'. The second group is defined as 'secondary resources' and comprise of 'natural' and 'human made resources' that play a secondary role in 'environmental sustainability'.

a. *Primary Resources:* Raw Materials, Consumables (Water), Energy (Oil; Gas; Coal…), Waste streams

b. *Secondary Resources*: Time, Human capital and Money capital

Since the strategic objective is to support "environmental sustainability", scope of the proposed indicator is limited to primary resources such as raw materials, water, energy and waste. It excludes secondary resources such as time, money (capital) or human capital.

On system boundaries, Huysman et al. (2015) observe that resource efficiency (RE) indicators have been developed for systems at micro-scale of specific processes and products to mesoscale and macro-scale of sectors and countries. At micro-scale, some indicators capture products and processes from factory entry gate to factory exit gate (Gate2Gate) while others consider full life cycle. Some indicators evaluate RE at regional or national level while others consider a more global perspective by including resources that are embodied in imported products.

The proposed indicator developed around the system boundary of a 'business unit' or a 'factory' is defined as the Gate2Gate ORE_{ft} indicator. It can measure 'operational resource effectiveness' for each 'business unit' or a 'factory' from its entry gate to exit gate (Gate2Gate). As in the case of the OEE, and as hypothesised, the scope of the proposed indicator is restricted to operational data. This aspect is substantiated by the industry survey (Fig 5). Also, an indicator that aims to be perfect by attempting to capture all aspects of environmental sustainability end up being too complex, lacks data availability and unless mandatory, is not accepted by the industry.

Table 4: System boundaries for mass balance (Jasch, 2002)

3.2.3 Elements of the proposed ORE_{ft} indicator:

The elements (variables) of the proposed indicator identified in Fig 3 are based on the circularity principles of the "5Rs of Resource Effectiveness" (Fig 2). To capture key elements of 'resource use' and 'waste generation', the framework considers the third 'R' that consists of 'recovery' options such as 'reuse' and 'reprocessing'. These 'recovery' options lead to the conversion of a 'waste' into a 'non-waste' (resource). The European waste directive 2008/98/EC, defines 'waste' as "any substance or object which the holder discards or intends to discard or is required to discard" (Directive, 2008). Elements of the proposed indicator takes into consideration the resource flows that could be measured in physical units of materials, energy and water flows as summarised in Table 4. To support the primary objective of 'environmental sustainability' only 'primary resources' categorised below are considered in the proposed indicator.

Virgin Resources:

a. Renewable virgin resources
b. Non-renewable virgin resources

Recovered Resources:

a. Reused (via repair, recondition, refurbish, remanufacture)
b. Reprocessed (upcycled, recycled, down-cycled)

Fig 2: 5Rs of Resource Effectiveness envisaged by (Gharfalkar et al., 2015)

Fig 3: Elements of proposed ORE$_{ft}$ indicator

3.2.4 Equations of the proposed Gate2Gate ORE$_{ft}$ indicator:

The concept behind 'Material Intensity per Unit Service' (MIPS or M1 in Table 2) is used for capturing each element of the proposed indicator identified in Fig 3. MIPS is calculated as mass of material input (MI) per total units of service (S) (Hinterberger and Schmidt-Bleek, 1999). Like MIPS, the proposed indicator captures consumption of different resources and generation of different wastes per unit of production in a factory. The proposed indicator is based on the resource flows that can be measured in physical units of materials, energy and water flow on the input side and flow of waste streams such as GHG, effluent, solid and hazardous waste on the output side (Fig 3). If product and/or process wise operational data for each element of the proposed ORE$_{ft}$ indicator identified in Fig 3 is available, then product and/or process wise ORE$_{ft}$ can be also assessed. But if it is not available, then all products manufactured in a factory need to be assigned the ORE$_{ft}$ of that factory.

Gate2Gate ORE$_{ft}$ = Resource Intensity per Unit x Waste Intensity per Unit

Gate2Gate ORE$_{ft}$ = RIPU x WIPU …………………………………………………………… (1)

On the resource consumption side equations, following abbreviations are used:

RIPU: Resource Intensity per Unit

WIPU: Waste Intensity per Unit

EIPU: Energy Intensity per Unit

MIPU: Material Intensity per Unit

W_{tr}IPU: Water Intensity per Unit

RIPU = EIPU + MIPU + W_{tr}IPU …………………………………….………………………… (2)

Where,

EIPU = (Energy Consumption) / (Production Units) ……………..…………. (2a)

MIPU = (Material Consumption) / (Production Units) ………..……………… (2b)

W_{tr}IPU = (Water Consumption) / (Production Units) …………….………… (2c)

Next level of elements of resource use as identified in Fig 3 are captured as below:

Energy = New Energy + Recovered Energy ……………………….…………... (2a.1)

New Energy = Renewable Energy + Non-renewable Energy ….…………..(2a.2)

As explained in the previous sections, consumption of only primary raw material (s) are considered in the consumption of materials.

Material = Virgin Material + Recovered Material

Virgin Material = Renewable Material + Non-renewable Material

Recovered Material = Reused Material + Reprocessed Material

Water Consumption = Fresh Water + Recovered Water

On the waste generation side equations, following abbreviations are used:

WIPU: Waste Intensity per Unit

GHGIPU: Greenhouse Gases Emissions Intensity per Unit

E_{ffl}IPU: Effluent Intensity per Unit

SWIPU: Solid Waste Intensity per Unit

E_{ffl}: Effluent

SW: Solid Waste

Haz: Hazardous

Nhaz: Non-hazardous

$WIPU = GHGIPU + SWIPU + E_{ffl}IPU$ ………………………………………………………………….. (3)

Where,

$GHGIPU$ = (Quantity of Greenhouse gas generated) / (Production Units)... (3a)

$SWIPU$ = (Quantity of Solid Waste generated) / (Production Units) ……….. (3b)

$E_{ffl}IPU$ = (Quantity of Effluent generated) / (Production Units) ………..…… (3c)

The next level of elements of waste generation include hazardous and non-hazardous waste. They are further classified into waste that is sent for recovery and waste that is sent for disposal. Greenhouse gases (GHG) are hazardous and are invariably released to the atmosphere. Therefore, GHG are captured under hazardous waste and does not include the next level of recovery and/or disposal. Once the practice of carbon capture is well established, these levels may be added to the downstream equations of GHG.

GHG = Haz GHG ………………………………………………………………………………. (3a.1)

E_{ffl} = Haz E_{ffl} + Nhaz E_{ffl} ……………………………………………………………….. (3b.1)

Haz E_{ffl} = Haz E_{ffl} for recovery + Haz E_{ffl} for disposal ………………………… (3b.1.1)

Nhaz E_{ffl} = Nhaz E_{ffl} for recovery + Nhaz E_{ffl} for disposal ……….…......... (3b.1.2)

SW = Haz SW + Nhaz SW ………………………………………………………………… (3c.1)

Haz SW = Haz SW for recovery + Haz SW for disposal ……………….…... (3c.1.1)

Nhaz SW = Nhaz SW for recovery + Nhaz SW for disposal …………… (3c.1.2)

To encourage ‘circularity’, each element of ‘resource consumption’ are allocated a different ‘incentive’ or a ‘discount’ or a ‘multiplying’ factor called ‘circularity’ factor. For example, in the case of energy use, manufacturers need greater incentive to the use of renewable energy over recovered energy than over non-renewable energy. Similarly, in the case of materials, there must be more incentive for use of renewable materials over recovered materials over non-renewable materials. Within the recovered materials category, ‘reused’ materials are considered more resource efficient than ‘reprocessed’ (recycled, upcycled, down-cycled) materials. Same logic is applied for the use of fresh and recovered water. Since there is no precedence or research in the use of such 'circularity factor', the use of ratios of Fibonacci numbers starting with 1 for deriving the 'circularity factor' has been proposed. These factors are used in the detailed equations of the proposed Gate2Gate ORE_{ft} indicator to encourage circularity / environmental sustainability (α = 1/1, β = 1/2, Y = 1/3, λ = 1/5).

'Circularity factors' are based on the hierarchy between different recovery options as proposed in the 'Hierarchy of Resource Use" by (Gharfalkar et al., 2015). Reuse could take place via repair and reuse, recondition and reuse, refurbish and reuse, remanufacture and reuse or any other operation and reuse. Reprocessing could include either recycling, upcycling or down cycling. Further, the hierarchy between various reuse options is based on the 'Hierarchy of Reuse Options" as proposed by (Gharfalkar et al., 2016).

Circularity factors for energy use:

The circularity factors for energy are based on the hierarchy of energy use where renewable energy is at the top, recovered energy at the middle and non-renewable energy at the bottom of the hierarchy.

Circularity factor for non-renewable Energy:

α = 1/1 = 1 -> no discount as it does not support environmental sustainability

Circularity factor for recovered Energy:

β = 1/2 = 0.5 -> medium discount for encouraging circularity

Circularity factor for renewable Energy:

Y = 1/3 = 0.33 -> maximum discount for supporting environmental sustainability

Circularity factor for material use:

The circularity factors for material use are based on the hierarchy of material use where renewable materials are at the top, followed by reused materials (repaired/reconditioned/refurbished/remanufactured), reprocessed materials (recycled/upcycled/downcycled) and non-renewable materials at the bottom of the hierarchy in the same order.

Circularity factor for non-renewable materials:

α = 1 -> no discount as it does not support environmental sustainability

Circularity factor for reprocessed materials:

β= 1/2 = 0.50 -> it is less resource efficient than reused

Circularity factor for reused materials:

Y = 1/3 = 0.33 -> More resource efficient than reprocessed

Circularity factor for renewable materials:

λ = 1/5 = 0.20 -> maximum discount for supporting environmental sustainability

Circularity factors for water use:

The circularity factors for water use are based on the hierarchy of water use where recovered water is at the top and fresh water the bottom of the hierarchy.

Circularity factor for fresh water: α = 1 -> No discount

Circularity factor for recovered water: β = 1/2 = 0.5 -> Maximum discount

With above inputs of circularity factors, the equations for energy, material and water consumption are as mentioned below:

Energy Consumption = α (Non-renewable) + β (Recovered) + Y (Renewable)

= (Non-renewable) + 0.5 (Recovered) + 0.33 (Renewable)

Material Consumption = α (Non-renewable) + β (Reprocessed) + Y (Reused) + λ (Renewable) = (Non-renewable) + 0.5 (Reprocessed) + 0.33 (Reused) + 0.20 (Renewable)

Water Consumption = α (Fresh) + β (Recovered) = (Fresh) + 0.5 (Recovered)

Circularity factors for waste generation:

The circularity factors for waste generation are based on the hierarchy of waste where non-hazardous waste for recovery is at the top, followed by non-hazardous waste for disposal, hazardous waste for disposal and hazardous waste for recovery at the bottom of the hierarchy in the same order. These circularity factors are used for differentiating between hazardous and non-hazardous waste at the primary level as well as waste going for recovery and waste going for disposal at the secondary level.

Circularity factors for Hazardous Waste:

For disposal: α = 1 -> No discount / incentive

For recovery: β= 1/2 = 0.50

Circularity factors for Non-Hazardous Waste:

For disposal: Y = 1/3 = 0.33

For recovery: λ = 1/5 = 0.20 -> maximum discount / incentive

The final equation for the Gate2Gate ORE_{ft} after consideration of circularity factor is as mentioned in equation number (4) and (5).

Gate2Gate ORE_{ft} = RIPU after circularity x WIPU after circularity ……………. (4)

RIPU after circularity = EIPU after circularity + MIPU after circularity + W_{tr}IPU after circularity

WIPU after circularity = GHGIPU after circularity + E_{ffl}IPU after circularity + SWIPU after circularity

Gate2Gate ORE_{ft} = ((Non-renewable energy) + 0.5 (Recovered energy) + 0.33 (Renewable energy) + (Non-renewable material) + 0.5 (Reprocessed material) + 0.33 (Reused material) + 0.20 (Renewable material) + (Fresh water) + 0.5 (Recovered water)) X ((GHG) + (Haz E_{ffl} for disposal) + 0.5 (Haz E_{ffl} for recovery) + 0.33 (Nhaz E_{ffl} for disposal) + 0.2 (Nhaz E_{ffl} for recovery) + (Haz SW for disposal) + 0.5 (Haz SW for recovery) + 0.33 (Nhaz SW for disposal) + 0.2

(Nhaz SW for recovery)) ……………………………………………………………………………………. (5)

Finally, the Gate2Gate ORE$_{ft}$ index of individual factory is derived as per equation (6). This equation ensures that the Gate2Gate ORE$_{ft}$ index can be measured on a scale of 0 to 1. It is assumed that higher the Gate2Gate ORE$_{ft}$ index score, better the manufacturing unit in terms of its resource effectiveness.

Gate2Gate ORE$_{ft}$ Index = 1 / (Gate2Gate ORE$_{ft}$)…………………………………………. (6)

3.3 Testing Stage:

Main objective of this stage is to test the validity of the proposed Gate2Gate ORE$_{ft}$ indicator. There are various definitions of validation. Oxford dictionary defines “to validate” as “to check or prove the validity or accuracy of”. Cambridge dictionary defines it as “to make something officially acceptable or approved, especially after examining it” and/or “to prove that something is correct”. Kirchner et al. (1996) defines ‘validity’ as the “adequacy for specific purpose”. Bockstaller and Girardin (2003) considers an indicator to be validated “if it is scientifically designed, if the information provided by it is relevant and if it is useful and used by the end users”.

General framework and methods for the validation of indicators at conceptual and output stage as suggested by Bockstaller and Girardin (2003) are summarised in Table 5. They clarify that the design or conceptual validation is important when the possibility of no other validation exist. Therefore, it is not necessary for a new indicator to be subjected to all types of validation.

a. *Conceptual validation*: To assess whether the indicator is scientifically founded.
b. *Output validation*: To assess the soundness of the outputs of the indicator.

Table 5: Framework for the validation of an indicator (Bockstaller and Girardin, 2003)

Following validation methods are adopted at the conceptual and output stage of the proposed Gate2Gate ORE$_{ft}$ indicator.

a. *Conceptual validation*: Review by experts' method is used for validating the concept of the proposed indicator. Manufactures are considered as the experts in this case and a web based "industry survey" is used to seek their inputs.

b. *Output validation:* Although 6 of the 86 manufacturers surveyed agreed to share data for testing of the indicator, only two shared their data: rubber products manufacturing unit and cast-iron foundry unit. The indicator is validated by establishing its relationship with consumption of resources per unit of production (RIPU) and generation of waste per unit of production (WIPU). The indicator is also validated by comparing the index with four other resource REMIs. It could not be compared with more REMIs due to lack of data as required for calculating other REMIs. Gate2Gate ORE_{ft} index of the two manufacturing units is also compared with each other to understand if and why one manufacturing unit is more resource effective than the other.

4. Results/Findings:

4.1. Findings of the analysis of 40 REMIs:

Outcome of the analysis of 40 REMIs using a set of quantitative and qualitative criteria is graphically depicted in Fig 4, Fig 5 and Fig 6. The graph in Fig 4 captures mean normalized scores of each of the 40 REMIs. These are further grouped into different blocks in two matrices as in Fig 5 & Fig 6. Proposed Gate2Gate ORE_{ft} indicator is also scored using the same set of criteria and plotted on the graph and the two matrices. In the 'Score versus Complexity Matrix' (Fig 5), the Y axis is grouped into three levels of scores: low score of 0 to less than 1, medium score between 1 to less than 2 and high score between 2 to 3. In the 'Data Availability versus Complexity Matrix' (Fig 6), the Y axis is grouped into three levels of data availability: low, medium and high. 'Low' indicates that a REMI is based on 100% assumptions; 'medium' indicates that it is based on a combination of operational data and assumptions, while 'high' indicates that it is based on 100% operational data. For both the matrices, the X axis is grouped into three levels of complexity: low, medium and high.

The analysis confirms that 75% of REMIs score below 1 against the mean normalised maximum possible score of 3 and the remaining 25% score between 1 to less than 2. Although, only two out of the 40 REMIs (M5 and M6) cross the half way mean normalized score of 1.5 (Fig 4), both, M5 and M6 are complex and not based on 100% operational data (Fig 5). Thirteen of the 40 REMIs (M2, M3, M12A, M12B, M14, M15, M16, M20, M21, M23, M24, M27 and M28) are low on complexity and high on data availability, but none of them simultaneously capture resource use and waste generation in their measurement (Fig 5; Fig 6 and Table 6).

Table 6: REMI grouping based on the aspects it captures in its measurement

Fig 4: Mean normalized scores of 40 REMIs and the proposed OREft indicator

Fig 5: Score versus Complexity Matrix

Fig 6: Data Availability vs Complexity Matrix

The three REMIs (M5, M6 & M15) that simultaneously capture both, resource consumption and waste generation in its measurements (Table 6) are high on complexity and not 100% based on easily available operational data. For example,

I. M5 (Ecological Footprint – Compound) relates to a country's use of resources to its land base. It involves estimation of net average per capita consumption of about fifty biotic resources, estimation of per capita land appropriated to produce each good or service and estimation of average annual per capita energy consumption for over hundred categories of traded goods. This is further converted to the amount of forested land necessary to sequester the emitted CO_2. Finally, the total ecological footprint is estimated by adding all the appropriated land areas. This is very complex, data intensive and low on data availability. Also, M5A is suitable for assessing resource efficiency only at national level.

II. M6 (Ecological Footprint – Component) is suitable for calculating footprint values for individual activities or components at local and personal level. But it is also complex, data intensive and low on data availability for all the 24 components that it takes into consideration in its measurement.

III. M15 (EMC) involves combining data from economy-wide material flow accounts such as direct material consumption (DMC) with data from life cycle analysis (LCA) by multiplying the mass of selected base materials with the LCA impact coefficients. Thirteen different impact categories of LCA are aggregated into one score by weighting. M13 is complex and not good on data availability.

IV. Although M13, M14, M16, M17, M18, M22, M23 and M30 are high on data availability and low on complexity, all of them are low on score.

V. Finally, while M34, M35, M36 and M37 are high on data availability and medium on complexity, none of them capture both, the resource use as well as waste generation in its measurement.

VI. None of the 40 REMIs provide incentives to encourage circularity in recovery, reprocessing or reuse of waste resources. With this major gap identified in the analysed REMIs, incentive/multiplying factor defined as circularity factors are used in the development of the proposed indicator.

VII. Analysis of 40 REMIs confirm that a REMI as per the hypothesis statement does not exist.

4.2. Results of the industry survey:

Key findings summarised here relate to the 86 responses by manufacturing, engineering and processing businesses in north England. These respondents are hereafter being called as “manufacturers”. Statistically, 86 responses represent the overall population of manufacturers in England at 94.1% expected incidence rate with +/- 5% error and 95% confidence level. The use of 90% Confidence levels with a margin of error of +/- 5% is considered reasonable for most audits / surveys (Bristol, 2015). Calculations of whether 86 responses represent the overall population of manufacturers in England are based on the sample size calculation mentioned below (Bristol, 2015):

$n = [c^2 \times N \times p \times (1-p)] / [(A^2 \times N) + (c^2 \times p \times (1-p)]$

Where,

n = sample size required

N = is the whole target population in question

p = is the average proportion of records expected to meet the various criteria

(1-p) is the average proportion of records not expected to meet the criteria

A = margin of error deemed to be acceptable (e.g. for 5% error either way, A = 0.05)

c = is a mathematical constant defined by the Confidence interval chosen (how sure we need to be of the result)

To be 95% sure of the result the constant c = 1.96

To be 90% sure of the result the constant c = 1.645

To be 80% sure of the result the constant c = 1.28

Three key findings of the industry survey are summarised below.

- 78% of manufacturers surveyed in north England agree that a good "resource effectiveness" indicator should include both, consumption of key natural resources and waste generation in its measurement (Fig 7).
- 54% of manufacturers surveyed in north England either strongly agree (16%) or agree (38%) that a good "resource effectiveness" indicator should be based on 100% operational data (Fig 8).
- Both the above findings substantiate the hypothesis statement.
- Considering current availability of data, 51% of manufacturers surveyed in north England recommend a system boundary of Factory Gate2Gate for the new indicator. Only 6% recommend a system boundary of Cradle2Gate for each product and 8% recommend a system boundary of Cradle2Grave for each product (Fig 9). This input is used to define the system boundary of the proposed resource effectiveness indicator as Factory Gate2Gate.

Fig 7: Elements of a good resource effectiveness indicator

Fig 8: Good resource effectiveness indicator should be based on 100% operational data

Fig 9: Preferred system boundary for a good resource effectiveness indicator

4.3. Results of case studies:

4.3.1. Gate2Gate ORE_{ft} index vs RIPU and WIPU:

Correlation between the resource intensity per unit (RIPU), waste intensity per unit (WIPU) and Gate2Gate ORE_{ft} index of the rubber products manufacturing and foundry unit is analysed. For both the units, it is observed that the Gate2Gate ORE_{ft} index is inversely proportional to RIPU as well as inversely proportional to WIPU of that manufacturing unit (Fig 10, 11, 12 and 13).

Fig 10: Rubber Unit: Resource Intensity Per Unit (RIPU) vs Gate2Gate ORE_{ft} Index

Fig 11: Rubber Unit: Waste Intensity Per Unit (WIPU) vs Gate2Gate ORE_{ft} Index

Fig 12: Foundry: Resource Intensity Per Unit (RIPU) vs Gate2Gate ORE_{ft} Index

Fig 13: Foundry: Waste Intensity Per Unit (WIPU) vs Gate2Gate ORE_{ft} Index

4.3.2 Comparison of Gate2Gate ORE_{ft} index of two manufacturing units:

Although it is not advisable to compare resource efficiency of two diverse manufacturing units such as a rubber product manufacturing and a foundry unit, a comparison of their Gate2Gate ORE_{ft} indices is carried out for academic purpose. It is assumed that the two units manufacture similar products. For a manufacturing unit to be resource efficient/productive than the other, it is necessary to have lower values of resource intensity per unit (RIPU) and/or waste intensity per unit (WIPU) vis-à-vis the other unit. RIPU is consumption of resources per unit of production and WIPU is generation of waste per unit of production. With this logic, the comparison of Gate2Gate ORE_{ft} index for these two units during 2013, 2014 and 2015 indicate that the first unit (in this case the rubber products manufacturing unit) is more resource efficient/productive than the second unit (foundry) in each year (Fig 14). Reasons why the first unit has a better Gate2Gate ORE$_{ft}$ index and therefore could be considered more resource efficient/productive than the second unit are mentioned below:

- 3 years' average consumption of resources per unit of production (RIPU) of the first unit is 6.00, which is 17% lower than that of the second unit whose average RIPU is 7.19 (Table 7).
- 3 years' average generation of wastes per unit of production (WIPU) of the first unit is 1.77, which is 22% lower than that of the WIPU of the second unit, which is 2.27 (Table 7).
- This means on an average; the first unit consume less resources per unit of production and generates lower waste per unit of production as compared to the second unit. Therefore, it may be inferred that the first unit is more resource efficient/productive than the second unit.

Table 7: RIPU, WIPU & Gate2Gate ORE$_{ft}$ Index of Rubber & Foundry Unit

Fig 14: Gate2Gate ORE$_{ft}$ index of Rubber Unit vs Foundry Unit

4.3.3 Comparison of Gate2Gate ORE$_{ft}$ index with other REMIs:

For validation/testing purpose, Gate2Gate ORE$_{ft}$ indices of the two manufacturing units are also compared with four REMIs described below:

a. *Resource productivity (M12A)*: Calculated as the monetary output per unit of all resources aggregated together. Since the two manufacturing units did not share monetary data, monetary output Is replaced with tons of production output. This Is divided by the aggregate of energy, material and water resources converted into equivalent tons.

b. *Material productivity (M20)*: Calculated as monetary output per unit of direct material consumed. Monetary output is replaced with tons of production output.

c. *Total material consumption (M21)*: It measures the total amount of materials directly used by a nation or a company or a business unit.

d. *Water productivity (M23)*: Calculated as monetary output per unit of fresh water consumed. Monetary output was replaced with tons of production output.

Values of the Gate2Gate ORE_{ft} index and the four REMIs for the foundry unit are summarised in table 8. Comparison of the Gate2Gate ORE_{ft} index with resource productivity (Fig 15), material productivity (Fig 16) and water productivity (Fig 17) shows similar trend between the compared indicators for 2012 to 2015. This is in line with the expectation that lower the resource/material/water productivity, lower the resource efficiency and vice-versa. Comparison of the Gate2Gate ORE_{ft} index with total material consumption shows an opposite trend (Fig 18). This is also in line with the expectation that lower the material consumption, higher the resource efficiency. Similar trends are observed for the plastic unit.

Table 8: Foundry unit: Gate2Gate ORE_{ft} Index vs REMIs

Fig 15: Foundry unit: Gate2Gate ORE_{ft} Index vs Resource Productivity M12A

Fig 16: Foundry unit: Gate2Gate ORE_{ft} Index vs Material Productivity M20

Fig 17: Foundry unit: Gate2Gate ORE_{ft} Index vs Water productivity M23

Fig 18: Foundry unit: Gate2Gate ORE_{ft} Index vs Total Material Consumption M21

5. Conclusions:

To summarize, none of the 40 analysed REMIs that were identified through the literature survey, capture both, the ‘resource use’, and ‘waste generation’ using 100% operational data in its measurement. Also, none of these REMIs provide incentives to encourage circularity in recovery, reprocessing or reuse of waste. 78% of surveyed manufacturers agreed that a good ‘resource effectiveness’ indicator should include both, consumption of key natural resources and waste generation in its measurement. Also, 54% of the manufacturers agree that a good ‘resource effectiveness' indicator should be based on operational data. Both these responses clearly validate the hypothesis. Finally, the inverse correlation established between the Gate2Gate ORE_{ft} index and the RIPU and the WIPU of a foundry and plastic products manufacturing unit, comparison of the Gate2Gate ORE_{ft} indices of these two units with each other and with four existing REMIs, validates the output generated by the new ORE_{ft} indicator. The ORE_{ft} indicator is a "new indicator" of "operational resource effectiveness" suitable for manufacturing units. Unlike many REMIs, the new ORE_{ft} indicator is based on readily available operational data, not assumptions. In addition to the fact that the proposed indicator captures "resource consumption" and "waste generation" in its measurement, inclusion of "circularity factors" that capture the circularity of resource use and recovery and reuse of waste streams is the key distinguishing feature of this indicator. In terms of its practical implications, the proposed indicator can be used for comparing the operational resource effectiveness of individual factories over a period as well as with other manufacturing units. It also captures useful information such as resource intensity per unit and waste intensity per unit, which also reflect operational resource efficiency or resource productivity that can be used to initiate improvement action. Adoption of this indicator across manufacturing supply chain can lead to an overall improvement in the resource efficiency, resource productivity, as well as resource effectiveness across the supply chain.

As far as the limitations of this research and the Gate2Gate ORE_{ft} indicator are concerned, testing of this indicator was limited to two dissimilar manufacturing units that shared data. The validation could have been more effective if more units manufacturing similar products had shared their operational data. Also, lack of availability of data for any supply chain, restricted the testing of this indicator to Gate2Gate boundary of each manufacturing unit. For a unit manufacturing a variety of products within the same campus, unless product or process wise resource consumption and waste generation data is available, this indicator cannot evaluate the resource effectiveness of individual products or processes within that campus. All products or processes within a campus are allocated the same resource effectiveness as that of the manufacturing unit. Also, the indicator considers consumption of only the primary raw materials. It does not differentiate between different raw materials as they are aggregated together by weight.

Suggestions for future investigations include, conducting an industry survey in other regions of the United Kingdom and/or Europe to create a database of Gate2Gate ORE_{ft} indices of similar and dissimilar manufacturing units. Further investigations may also be carried out targeting specific industrial segments such as the foundry or the plastic injection moulding units. This may help in identifying units with high Gate2Gate ORE_{ft} index, whose best practices could then be shared within the industry segment for overall improvement of that segment.

The linear system of 'make-use-dispose' is not environmentally sustainable. To achieve real long-term environmental sustainability, evolution of 'closed loop resource effective business models' is inevitable. These business models are likely to have renewable natural resources as inputs and outputs that are environmentally benign. This goal of environmental sustainability can be achieved if resource effectiveness is assessed at each stage of a product life cycle. Manufacturing is just one stage of this cycle. It may not be important how accurate or precise an indicator is but whether it gives some indication of resource effectiveness that could be used for initiating improvement actions. The proposed ORE_{ft} indicator is a new indicator that could be used by manufacturers for achieving this objective.

References:

ABDUL RASHID, S. H., EVANS, S. & LONGHURST, P. 2008. A comparison of four sustainable manufacturing strategies. *International Journal of Sustainable Engineering,* 1**,** 214-229.

BERNOLAK, I. 1997. Effective measurement and successful elements of company productivity: The basis of competitiveness and world prosperity. *International Journal of Production Economics,* 52**,** 203-213.

BOCKSTALLER, C. & GIRARDIN, P. 2003. How to validate environmental indicators. *Agricultural Systems,* 76**,** 639-653.

BRISTOL. 2015. *Sample Size Calculator* [Online]. Bristol University. Available: www.uhbristol.nhs.uk/files/nhs-ubht/sample_size_calculator.xls [Accessed 2015].

BURRITT, R. L. & SAKA, C. 2006. Environmental management accounting applications and eco-efficiency: case studies from Japan. *Journal of Cleaner Production,* 14**,** 1262-1275.

DALY, H. E. 1996. Operationalizing Sustainable Development by Investing in Natural Capital. *Beyond Growth: The Economics of Sustainable Development.* Boston: Beacon Press Books.

DIFFEN. 2015. *Effectiveness vs. Efficiency* [Online]. Seattle: Diffen. Available: http://www.diffen.com/difference/Effectiveness_vs_Efficiency [Accessed 10.01.2015 2015].

DIRECTIVE 2008. Directive 2008/98/EC of The European Parliament And of The Council on Waste and Repealing Certain Directives. Official Journal of the European Union.

DUFLOU, J. R., SUTHERLAND, J. W., DORNFELD, D., HERRMANN, C., JESWIET, J., KARA, S., HAUSCHILD, M. & KELLENS, K. 2012. Towards energy and resource efficient manufacturing: A processes and systems approach. *CIRP Annals - Manufacturing Technology,* 61**,** 587-609.

EC 2011. Roadmap to a Resource Efficient Europe: Communication from The Commission To The European Parliament, The Council, The European Economic and Social Committee and The Committee of The Regions. *In:* COMMISSION, E. (ed.). Brussels: European Commission.

EPA-TASMANIA. 2013. *Resource Efficiency* [Online]. Environment Protection Agency - Tasmania, Australia. Available: http://epa.tas.gov.au/sustainability/resource-efficiency [Accessed 8th August 2014].

EUROMINES 2011. Position on Resource Efficiency. *In:* EUROMINES (ed.) www.euromines.org. European Association of Mining Industries Metal Ores & Industrial Minerals.

EUROSTAT 2013. Resource Efficiency Scoreboard: Thirty indicators to measure resource efficiency in the EU. 186/2013 ed.: Eurostat Press Office.

FEARNE, A. & FOWLER, N. 2006. Efficiency versus effectiveness in construction supply chains: the dangers of "lean" thinking in isolation. *Supply Chain Management,* 11**,** 283-287.

GAUSSIN, M., HU, G., ABOLGHASEM, S., BASU, S., SHANKAR, M. R. & BIDANDA, B. 2013. Assessing the environmental footprint of manufactured products: A survey of current literature. *International Journal of Production Economics,* 146**,** 515-523.

GHARFALKAR, M., ALI, Z. & HILLIER, G. 2016. Clarifying the disagreements on various reuse options: Repair, recondition, refurbish and remanufacture. *Waste Management & Research*.

GHARFALKAR, M., COURT, R., CAMPBELL, C., ALI, Z. & HILLIER, G. 2015. Analysis of waste hierarchy in the European waste directive 2008/98/EC. *Waste Management,* 39**,** 305-313.

HERNANDEZ, A. G. & CULLEN, J. M. 2016. Unlocking Plant-level Resource Efficiency Options: A Unified Exergy Measure. *Procedia CIRP,* 48**,** 122-127.

HINTERBERGER, F. & SCHMIDT-BLEEK, F. 1999. Dematerialization, MIPS and Factor 10 Physical sustainability indicators as a social device. *Ecological Economics,* 29**,** 53-56.

HIRSCHNITZ-GARBERS, M. & SREBOTNJAK, T. 2012. Ecologic Policy Briefs - Integrating Resource Efficiency, Greening of Industrial Production and Green Industries - Scoping of and recommendations for effective indicators. *In:* KRAEMER, R. A. & MULLER-KRAENNER, S. (eds.). Germany: Ecologic Institute for International and European Environmental Policy.

HUYSMAN, S., SALA, S., MANCINI, L., ARDENTE, F., ALVARENGA, R. A. F., DE MEESTER, S., MATHIEUX, F. & DEWULF, J. 2015. Toward a systematized framework for resource efficiency indicators. *Resources, Conservation and Recycling,* 95**,** 68-76.

HUYSVELD, S., DE MEESTER, S., VAN LINDEN, V., MUYLLE, H., PEIREN, N., LAUWERS, L. & DEWULF, J. 2015. Cumulative Overall Resource Efficiency Assessment (COREA) for comparing bio-based products with their fossil-derived counterparts. *Resources, Conservation and Recycling,* 102**,** 113-127.

JANSEN, J. 2013. Resouce Efficiency: What does it mean and why is it relevant? - Policy Brief. Petten, The Netherlands: ECN Policy Studies.

JASCH, C. 2002. How to define corporate environmental costs. *In:* TUKKER, A. & TNO-STB, D., THE NETHERLANDS (eds.) *Environmental Management Accounting: Informational and Institutional Developments.* The Netherlands: Kluwer Academic Publishers.

KAO, C., CHEN, L.-H., WANG, T.-Y., KUO, S. & HORNG, S.-D. 1995. Productivity improvement: Efficiency approach vs effectiveness approach. *Omega,* 23**,** 197-204.

KIRCHNER, J. W., HOOPER, R. P., KENDALL, C., NEAL, C. & LEAVESLEY, G. 1996. Testing and validating environmental models. *Science of the Total Environment,* 183**,** 33-47.

KITAJIMA, T., SAWANISHI, H., TAGUCHI, M., TORIHARA, K., HONMA, O. & MISHIMA, N. 2015. A Proposal on a Resource Efficiency Index for EEE. *Procedia CIRP,* 26**,** 607-611.

MODI, S. B. & MISHRA, S. 2011. What drives financial performance–resource efficiency or resource slack? *Journal of Operations Management,* 29**,** 254-273.

MOFFATT, I., HANLEY, N., ALLEN, S. & FUNDINGSLAND, M. 2001. Sustainable Prosperity: Measuring Resource Efficiency.

NEELY, A., GREGORY, M. & PLATTS, K. 1995. **Performance measurement** system design: a literature review and research agenda. *International Journal of Operations & Production Management,* 15**,** 80-116.

PARKER, D. 2007. An Analysis of the Spectrum of Reuse - A Component of the Remanufacturing Pilot for Defra BREW Programme. United Kingdom: Oakdene Hollins Ltd.

SPUERK, S., DROBE, M. & LOTTERMOSER, B. G. 2017. Evaluating resource efficiency at major copper mines. *Minerals Engineering,* 107**,** 27-33.

STEFAN, T. 2004. Performance measurement: from philosophy to practice. *International Journal of Productivity and Performance Management,* 53**,** 726-737.

TILTON, J. E. 2003. Chapter 1: The Road Ahead. *On Borrowed Time? Assessing the Threat of Mineral Depletion.* Washington, DC: Resources for the Future.

UNEP 2010. Resource Efficiency - Fact Sheet. Paris: United Nations Environment Programme.

UNEP. 2014. *UNEP's Resource Efficiency Programme* [Online]. UNEP. Available: http://www.unep.org/resourceefficiency/Home/UNEPsResourceEfficiencyProgramme/tabid/55552/Default.aspx [Accessed 7th July 2014].

VALERO, A., VALERO, A. & CALVO, G. 2015. Using thermodynamics to improve the resource efficiency indicator GDP/DMC. *Resources, Conservation and Recycling,* 94**,** 110-117.

Tables Document

Criterion/Description	Total Documents
Articles / documents published in English language between 1st January 1987 to 14th July 2017	149
Scholarly and peer reviewed Journal Articles, Conference Proceedings, Dissertation/Thesis, Book Chapter and Reports	90
Articles / Documents restricted to engineering, environmental sciences, business and ecology disciplines	26

Table 1: Summary of database search

REMI	Resource Efficiency Measure and/or Indicator ((REMI)	Reference Document/Article
M1	MIPS (Material Intensity Per Service Unit)	(Moffatt et al., 2001)
M2	Factor Four (Eco efficiency)	(Moffatt et al., 2001)
M3	Factor Ten (Eco efficiency)	(Moffatt et al., 2001)
M4	Environmental Space	(Moffatt et al., 2001)
M5	Ecological Footprint (Compound Based)	(Moffatt et al., 2001)
M6	Ecological Footprint (Component Based)	(Moffatt et al., 2001)
M7	Human Appropriated Net Primary Production	(Moffatt et al., 2001)
M8	Assimilative Capacity	(Moffatt et al., 2001)
M9	Asset Balances of Environmental Capital	(Moffatt et al., 2001)
M10	Safe Minimum Standards (SMS)	(Moffatt et al., 2001)
M11	Cost effectiveness in Pollution Control	(Moffatt et al., 2001)
M12	Resource Utilization Rates with Economic Optima	(Moffatt et al., 2001)
M13	Resource Productivity (Classical Y/ m measure)	(Moffatt et al., 2001)
M14	Resource Productivity (Classical Y/e measure)	(Moffatt et al., 2001)
M15	Environmentally Weighted Material Consumption (EMC)	(Hirschnitz-Garbers and Srebotnjak, 2012)
M16	Energy Intensity by Sector	(Hirschnitz-Garbers and Srebotnjak, 2012)
M17	Production Based CO_2 Productivity	(Hirschnitz-Garbers and Srebotnjak, 2012)
M18	Water Consumption by Sector (annual)	(Hirschnitz-Garbers and Srebotnjak, 2012)
M19	Sustainable Process Index (SPI)	(Hirschnitz-Garbers and Srebotnjak, 2012)
M20	Water Absorption Rate & Water Stress	(Hirschnitz-Garbers and Srebotnjak, 2012)
M21	Corporation's turnover, value added and exports of the environmental goods and	(Hirschnitz-Garbers and Srebotnjak, 2012)

	services sector	
M22	Resource Productivity (Lead Resource Efficiency Indicator (GDP/DMC)	(Valero et al., 2015), (Hirschnitz-Garbers and Srebotnjak, 2012)
M23	Total Material Consumption (TMC)	(Hirschnitz-Garbers and Srebotnjak, 2012)
M24	Land Indicator – Productivity of Built-up Area	(Eurostat, 2013)
M25	Water Indicator – Water Productivity	(Eurostat, 2013)
M26	Water Indicator – Water Exploitation Index	(Eurostat, 2013)
M27	Carbon Indicator – Per Capita GHG Emissions	(Eurostat, 2013)
M28	Carbon Indicator – Energy Productivity	(Eurostat, 2013)
M29	Carbon Indicator – Energy Dependence	(Eurostat, 2013)
M30	Carbon Indicator – Share of Renewable Energy in Gross Energy Consumption	(Eurostat, 2013)
M31	Resource Efficiency Index for EEE	(Kitajima et al., 2015)
M32	Weighted Relative Resource Intensity Index	(Spuerk et al., 2017)
M33	Cumulative Overall Resource Efficiency Indicator (COREA)	(Huysveld et al., 2015)
M34	Resource Efficiency	(Hernandez and Cullen, 2016)
M35	Inventory Resource Efficiency	(Modi and Mishra, 2011)
M36	Production Resource Efficiency	(Modi and Mishra, 2011)
M37	Marketing Resource Efficiency	(Modi and Mishra, 2011)
M38	Ecological Product Efficiency	(Burritt and Saka, 2006)
M39	Ecological Function Efficiency	(Burritt and Saka, 2006)
M40	Eco-efficiency	(Burritt and Saka, 2006)

Table 2: REMIs identified through literature survey

No	Category Title	Max Score	Mean Normalized Score
1	**S**uitability-Feasibility-Scope of Measurement	12	12/22 = 0.55
2	Resource consumption related	39	39/22 = 1.77
3	Waste generation related	15	15/22 = 0.68
	Total Score	**66**	**3.00**
	Category Average or Category Mean = 66 / 3	**22.00**	

Table 3: Categories of criteria used for the analysis of REMI

Input	System Boundaries	Output
Materials Energy Water	Nations Regions Corporations Processes Products	Products Waste Emissions

Table 4: System boundaries for mass balance (Jasch, 2002)

Type of validation	Question	Methods of validation
Conceptual validation	Is it scientifically founded?	• Peer review • Review by experts • Comparison of approaches
Output validation (Empirical validation)	Is it realistic or does it inform about the reality?	• Validation through comparison with a set of measured data. • Global expert validation

Table 5: Framework for the validation of an indicator (Bockstaller and Girardin, 2003)

Captures Resource Use Only	Captures Waste Generation Only	Simultaneously Captures Resource Use & Waste Generation
M1, M2, M3, M7, M9, M12, M13, M18, M19, M20, M22, M23, M24, M25, M26, M28, M29, M30, M31, M32, M33, M34, M35, M36, M37	M4, M8, M11, M14, M16, M17, M27, M38, M39, M40	M5, M6, M15 Proposed Gate2Gate ORE$_{ft}$ Indicator

Table 6: REMI grouping based on the aspects it captures in its measurement

Year	RIPU		WIPU		Gate2Gate ORE$_{ft}$ Index	
	Rubber	Foundry	Rubber	Foundry	Rubber	Foundry
2013	6.55	7.21	2.34	2.32	0.07	0.06
2014	6.17	6.71	1.61	2.08	0.10	0.07
2015	5.28	7.64	1.36	2.40	0.14	0.05
Average	**6.00**	**7.19**	**1.77**	**2.27**	**0.09**	**0.06**

Table 7: RIPU, WIPU & Gate2Gate ORE$_{ft}$ Index of Rubber & Foundry Unit

REMI	Code	2012	2013	2014	2015
Gate2Gate ORE$_{ft}$ Index	ORE$_{ft}$	0.057	0.060	0.072	0.055
Resource Productivity	M12A	0.110	0.113	0.123	0.107
Material Productivity	M20	0.136	0.140	0.146	0.132
Total Material Consumption	M21	2015	2106	2516	2001
Water Productivity	M23	0.688	0.724	0.953	0.673

Table 8: Foundry unit: Gate2Gate OREft vs REMIs

Figures

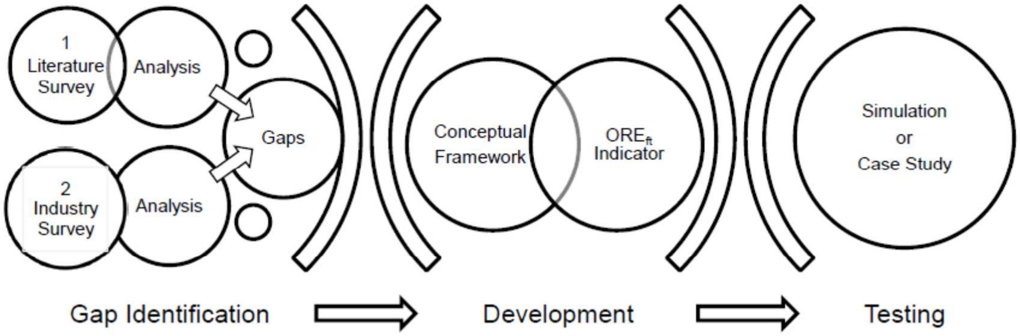

Fig 1: Research methodology

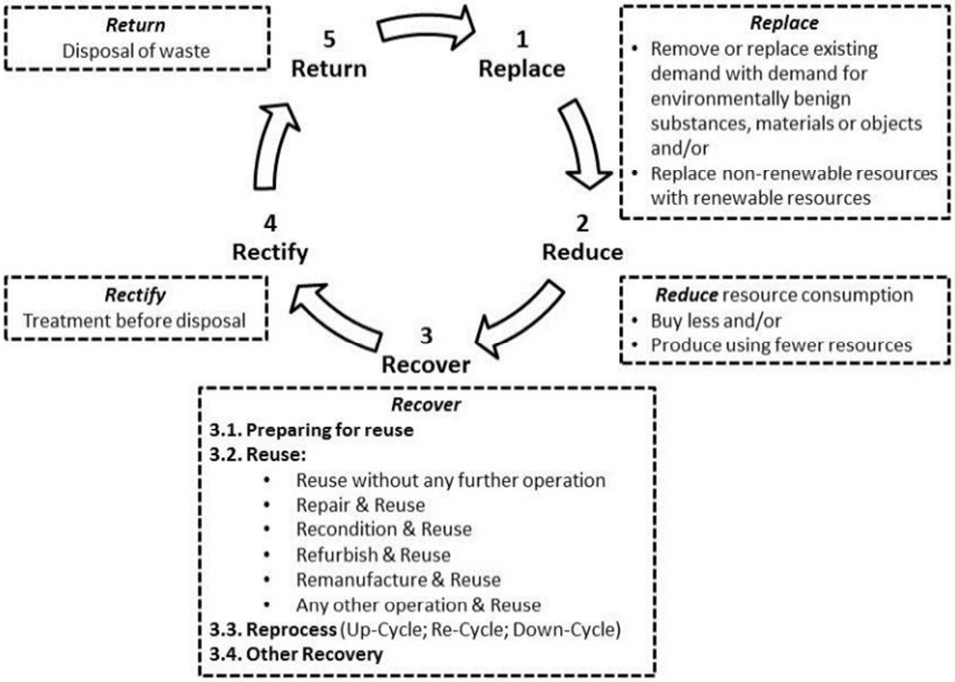

Fig 2: 5Rs of Resource Effectiveness envisaged by (Gharfalkar et al., 2015)

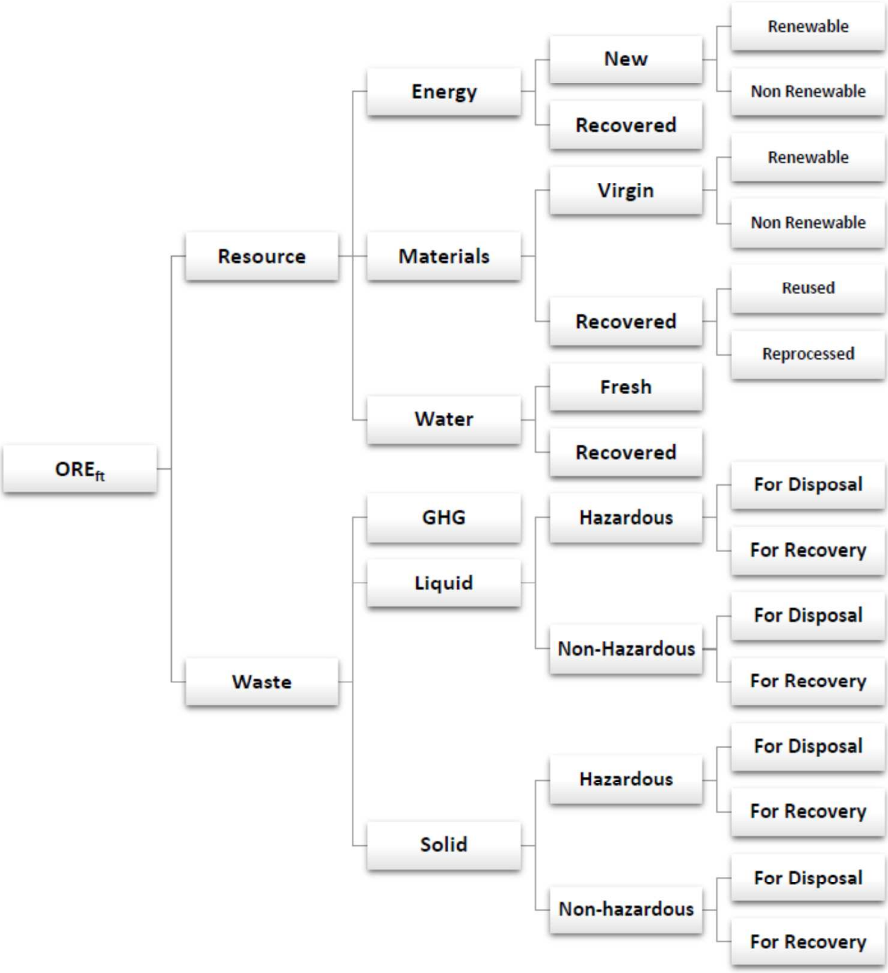

Fig 3: Elements of proposed ORE_{ft} indicator

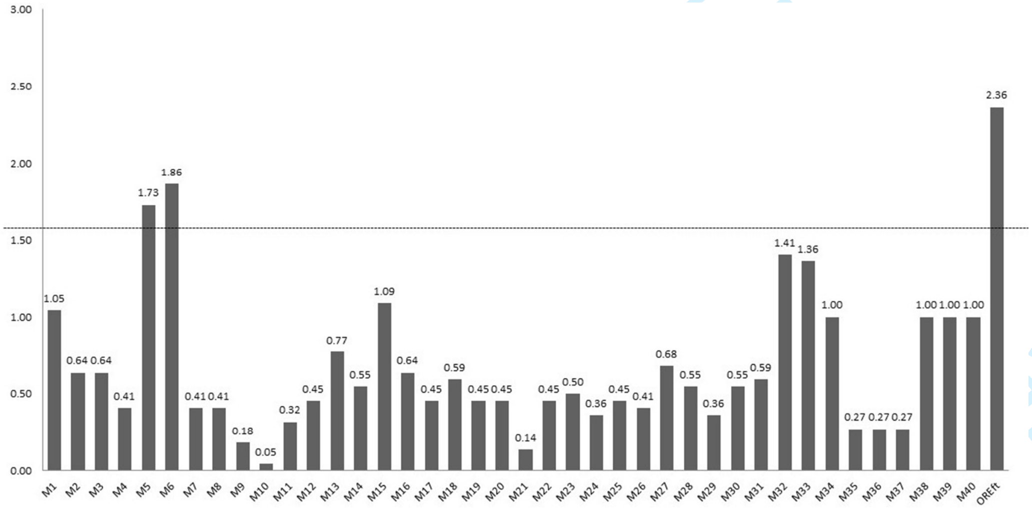

Fig 4: Mean normalized scores of 40 REMIs and the proposed OREft indicator

	Low Complexity	Medium Complexity	High Complexity
High Score 2 - 3		ORE_{ft}	
Medium Score 1 - <2		M1, M32, M34	M5, M6, M15, M33, M38, M39, M40
Low Score 0 - < 1	M2, M3, M13, M14, M16, M17, M18, M22, M23, M25, M26, M29, M30	M20, M21, M27, M28, M35, M36, M37	M4, M7, M8, M9, M10, M11, M12, M19, M24, M31

Fig 5: Score versus Complexity Matrix

	Low Complexity	Medium Complexity	High Complexity
High Data Av	M13, M14, M16, M17, M18, M22, M23, M30	M34, M35, M36, M37, ORE_{ft}	
Medium Data Av	M2, M3, M25, M26, M29	M1, M20, M21, M27, M28, M32	M4, M5, M6, M7, M8, M9, M10, M11, M12, M15, M31, M33, M38, M39, M40
Low Data Av			M19, M24

Fig 6: Data Availability vs Complexity Matrix

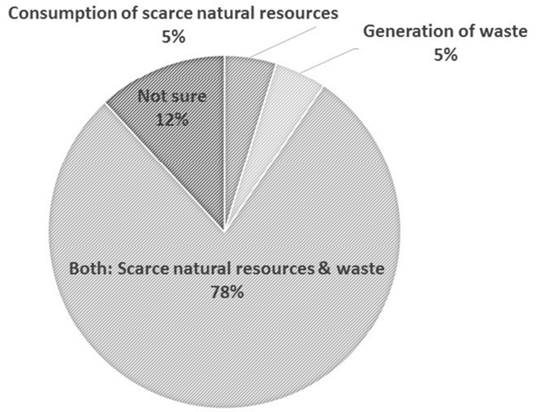

Fig 7: Elements of a good resource effectiveness indicator

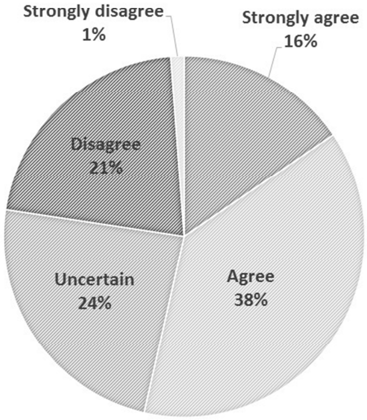

Fig 8: Good resource effectiveness indicator should be based on 100% operational data

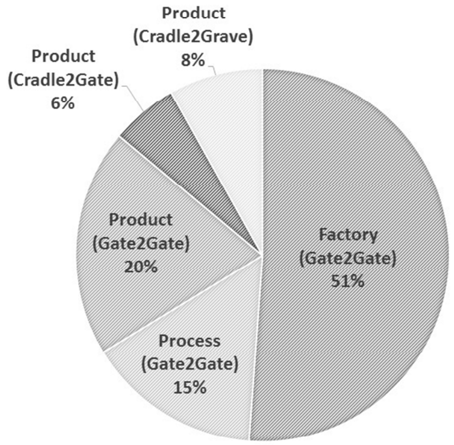

Fig 9: Preferred system boundary for a good resource effectiveness indicator

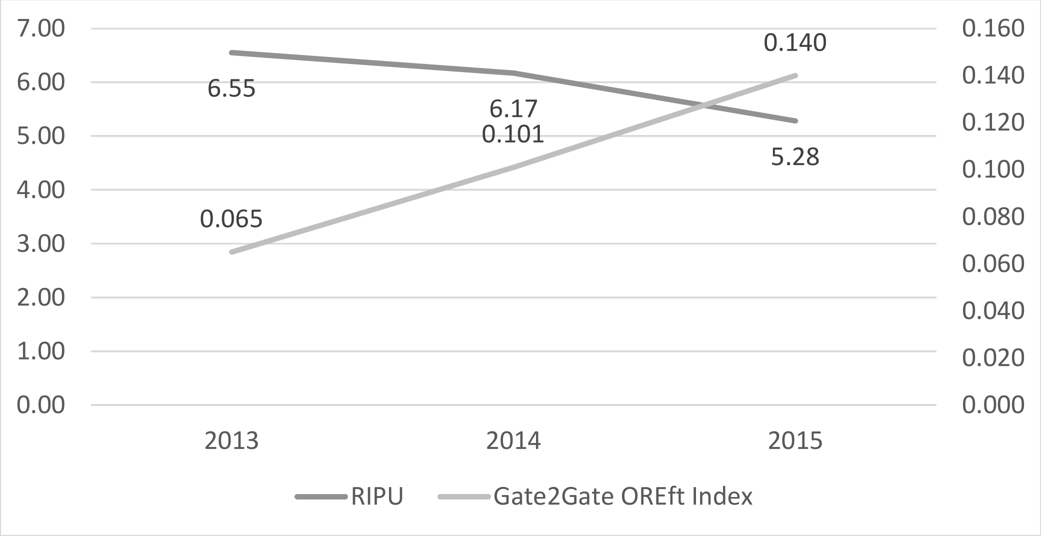

Fig 10: Rubber Unit: Resource Intensity Per Unit (RIPU) vs Gate2Gate ORE$_{ft}$ Index

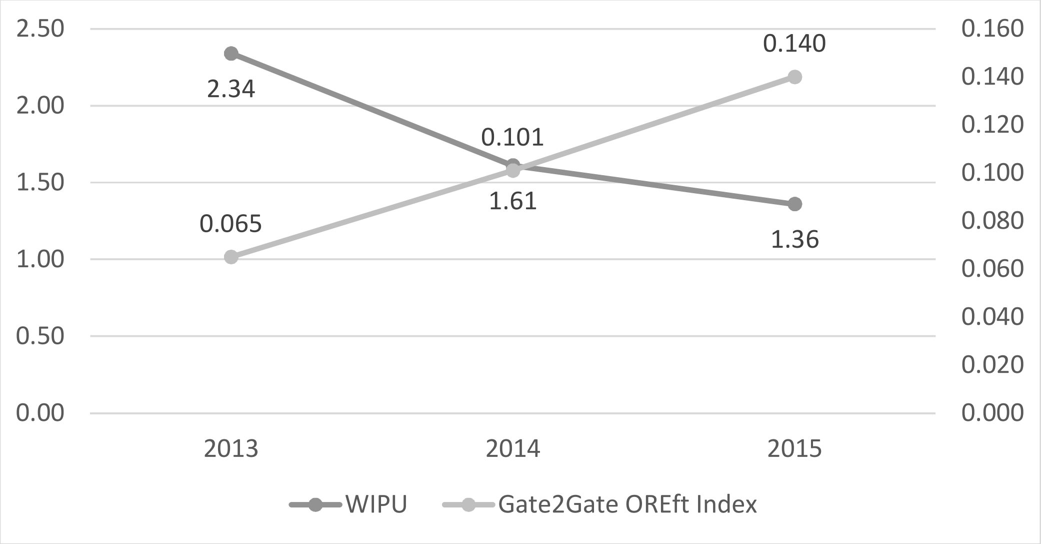

Fig 11: Rubber Unit: Waste Intensity Per Unit (WIPU) vs Gate2Gate ORE$_{ft}$ Index

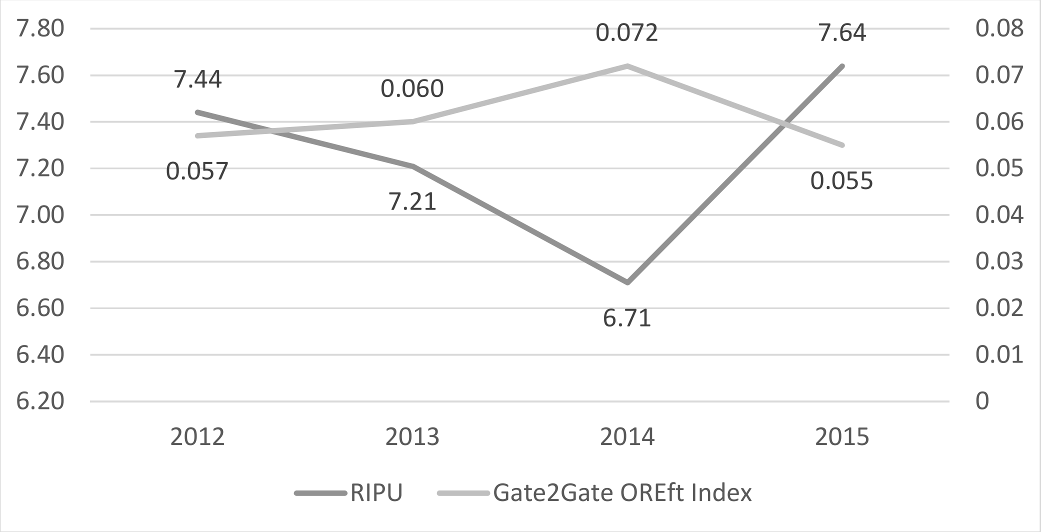

Fig 12: Foundry: Resource Intensity Per Unit (RIPU) vs Gate2Gate ORE$_{ft}$ Index

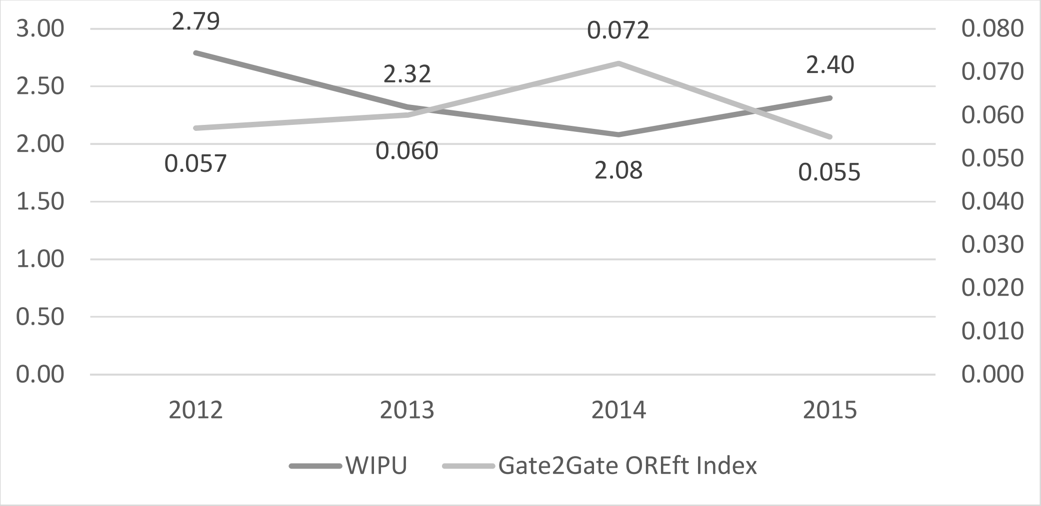

Fig 13: Foundry: Waste Intensity Per Unit (WIPU) vs Gate2Gate ORE$_{ft}$ Index

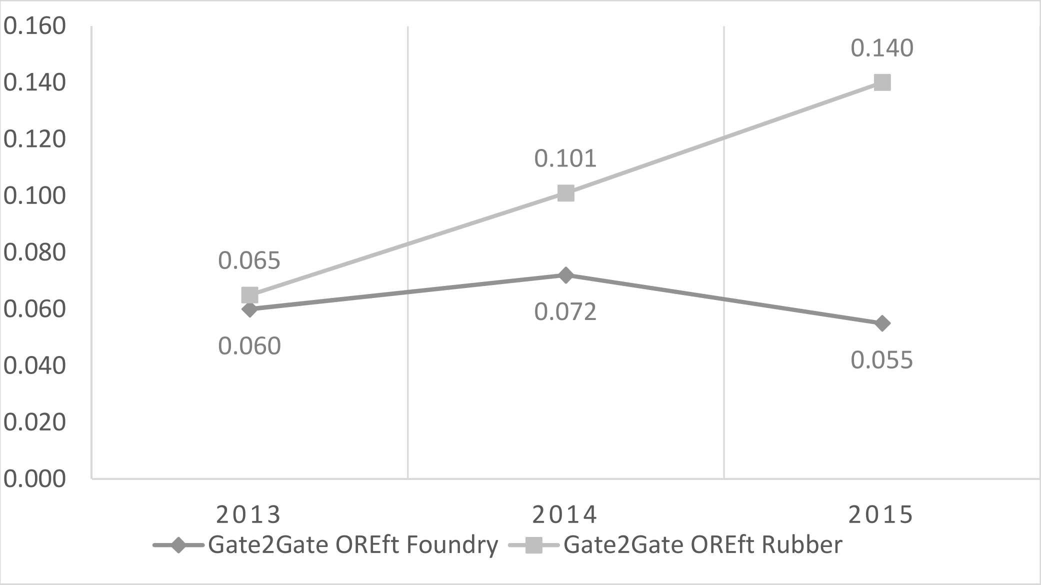

Fig 14: Gate2Gate ORE$_{ft}$ index of Rubber Unit vs Foundry Unit

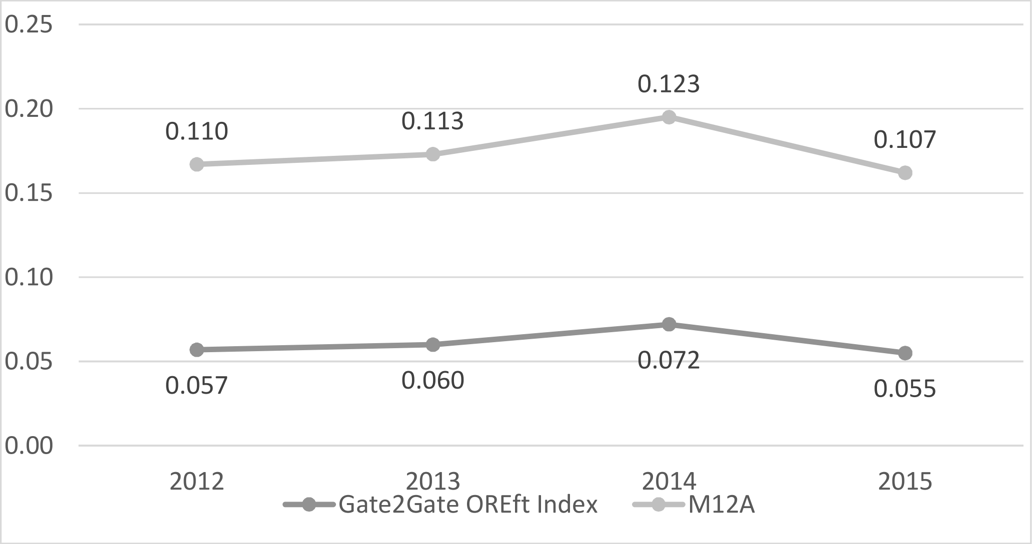

Fig 15: Foundry unit: Gate2Gate ORE$_{ft}$ Index vs Resource Productivity M12A

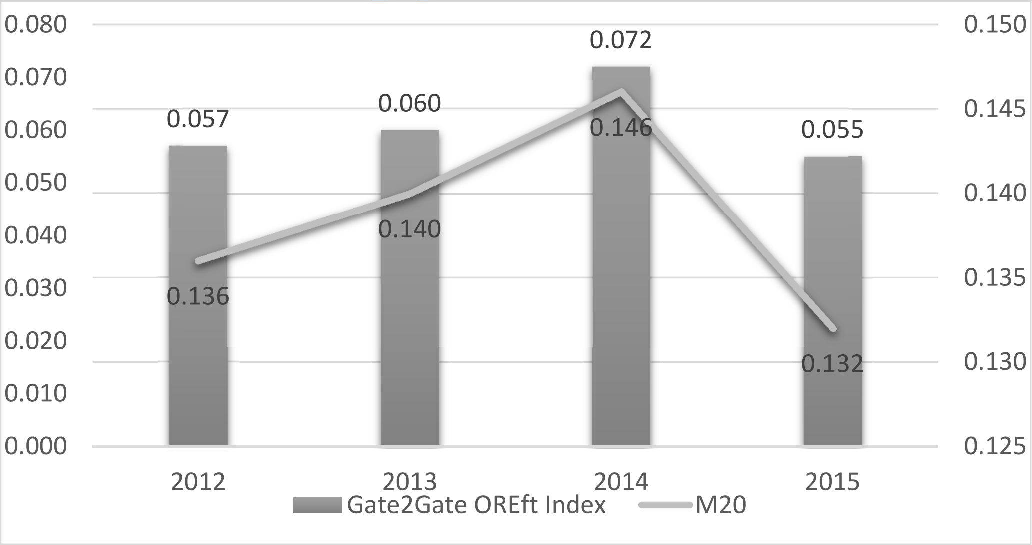

Fig 16: Foundry unit: Gate2Gate ORE$_{ft}$ Index vs Material Productivity M20

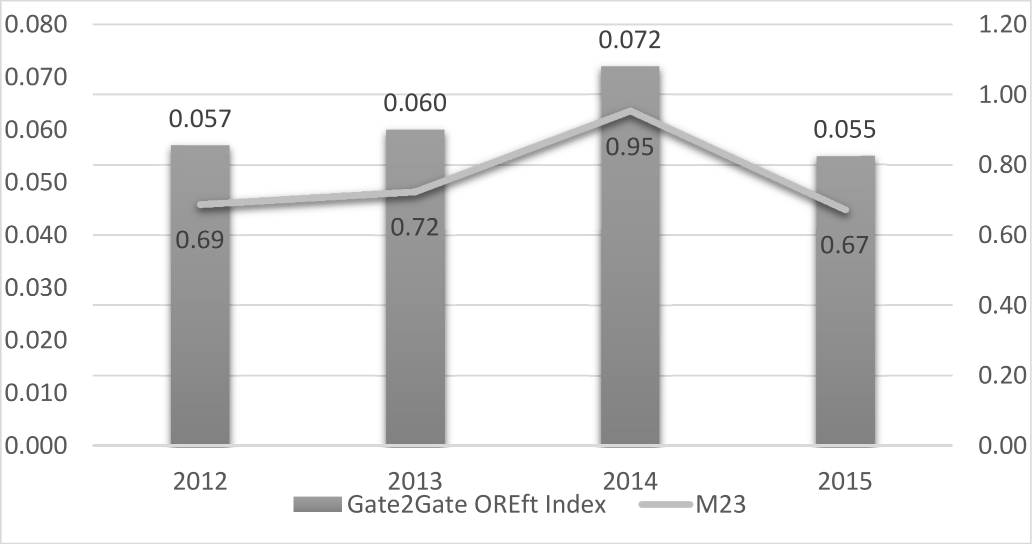

Fig 17: Foundry unit: Gate2Gate ORE_{ft} Index vs Water productivity M23

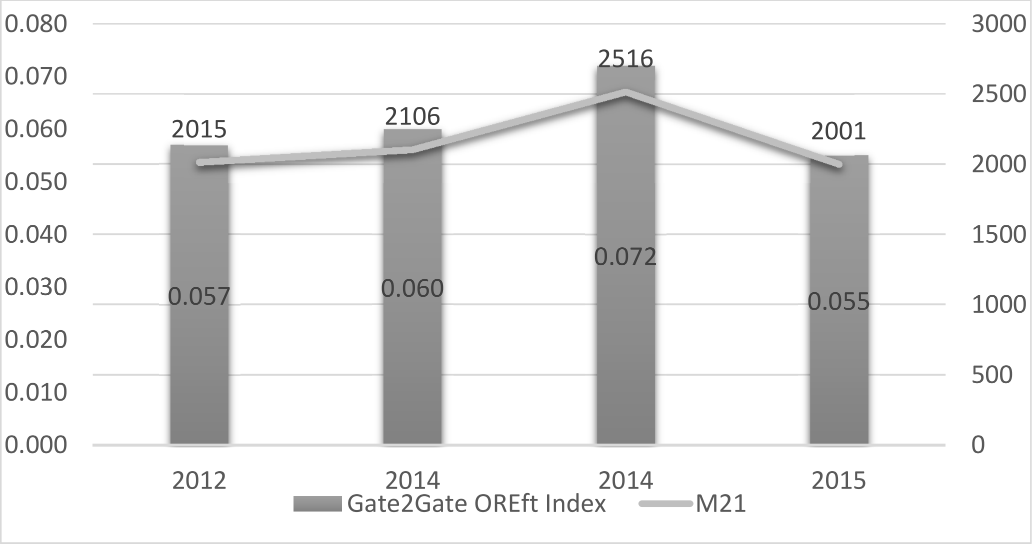

Fig 18: Foundry unit: Gate2Gate ORE_{ft} Index vs Total Material Consumption M21