CHALLENGES IN TRACKING WASTE REDUCTION PERFORMANCE IMPROVEMENT IN MANUFACTURING PLANTS

Subodh Chaudhari, Oak Ridge National Laboratory
Alexandra Botts, Oak Ridge National Laboratory
Sachin Nimbalkar, Oak Ridge National Laboratory
Cory Tatarzyn, General Motors
Tina Burry, General Motors
Thomas Wenning, Oak Ridge National Laboratory

Abstract

The recently released Circularity Gap Report 2023 by Circle Economy Foundation found that the circularity score for the global economy is declining. This indicates that material extraction from virgin sources is climbing over earlier years. As per data released by US Geological Survey, material use in the US economy has increased exponentially with the expanding US economy over last century. EPA tracked municipal solid waste from 1960 to 2018 and found that 50% of the waste is destined for landfills. EPA estimates that US industry is responsible for 2.7 billion ton of solid non-hazardous waste annually in our mostly linear economy model. The circular economy framework aims at decoupling economic value generation from virgin materials extraction from nature. The linear model of material extraction and disposal at end of life is highly unsustainable. Manufacturing companies have realized this and in their commitments to sustainability are adopting ambitious waste reduction targets. Through Better Plants program US Department of Energy has established Waste Reduction Network where it is offering technical assistance to partners to achieve these ambitious waste reduction goals.

Basic requirements of establishing a target include identifying a baseline, quantifying waste performance, and measuring progress over time. One problem faced by industry is the unstandardized metrics to quantify waste performance that may not be well suited to demonstrate progress. In this paper, we research methods traditionally used to measure waste performance and highlight advantages, gaps and limitations of each method. Suitability of the methods applicable to different manufacturing circumstances are also examined. Finally, we present a case study of a large manufacturer that faced inconsistencies in their tracked measurement metric. A solution was proposed to alter the methodology to enable more accurate waste performance tracking against a baseline.

Keywords: Circular economy, Waste reduction, Sustainable manufacturing, Tracking

1 Significance of Waste Reduction

Manufacturing is an essential sector of the US economy which provides numerous benefits but is experiencing pressures on many fronts such as environmental performance, quality, material availability, resource costs, laws and regulations among others. Many of these issues are intertwined one way or another with waste performance of the manufacturing operations. Waste generation is as old as manufacturing itself, but it has taken increased significance with the onset of sustainable development goals (SDG) adopted by corporations in modern context. The manufacturing business model is largely linear, i.e., “Extract-Make-Use-Dispose” approach that does not consider environmental impact of production, use, and end of life of products. As waste is deeply intertwined with manufacturers resource performance the implied relevance of waste related initiatives such as UN SDG-12 and circular economy (CE) is high. These initiatives improve long term outlook of the business and create significant competitive advantage.

1.1 Waste Statistics

In a linear economy, as industrial output increases, so does the waste. US economy has expanded steadily over the last century. Department of Commerce looked at the manufacturing activity in US and found that manufacturing value added has increased consistently since 1970 [1]. The manufacturing activity is in part dependent on material extraction from natural sources in addition to imports and end-of-life recycling in the economy. Figure 1 shows the raw material flows in the US gradually increasing over the last century except during the recession periods. The total raw material flow in 2020 was 3.18 Gt[1]/yr, dampened slightly as a result of short recession in initial period of COVID-19 pandemic. However, the data indicate that the flow resumed during 2021 and 2022 [2], [3]. The material flows shown exclude imported materials and finished goods.

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[1] All figures in Metric Tons. Gt = Billion Metric Ton, Mt = Million Metric Ton

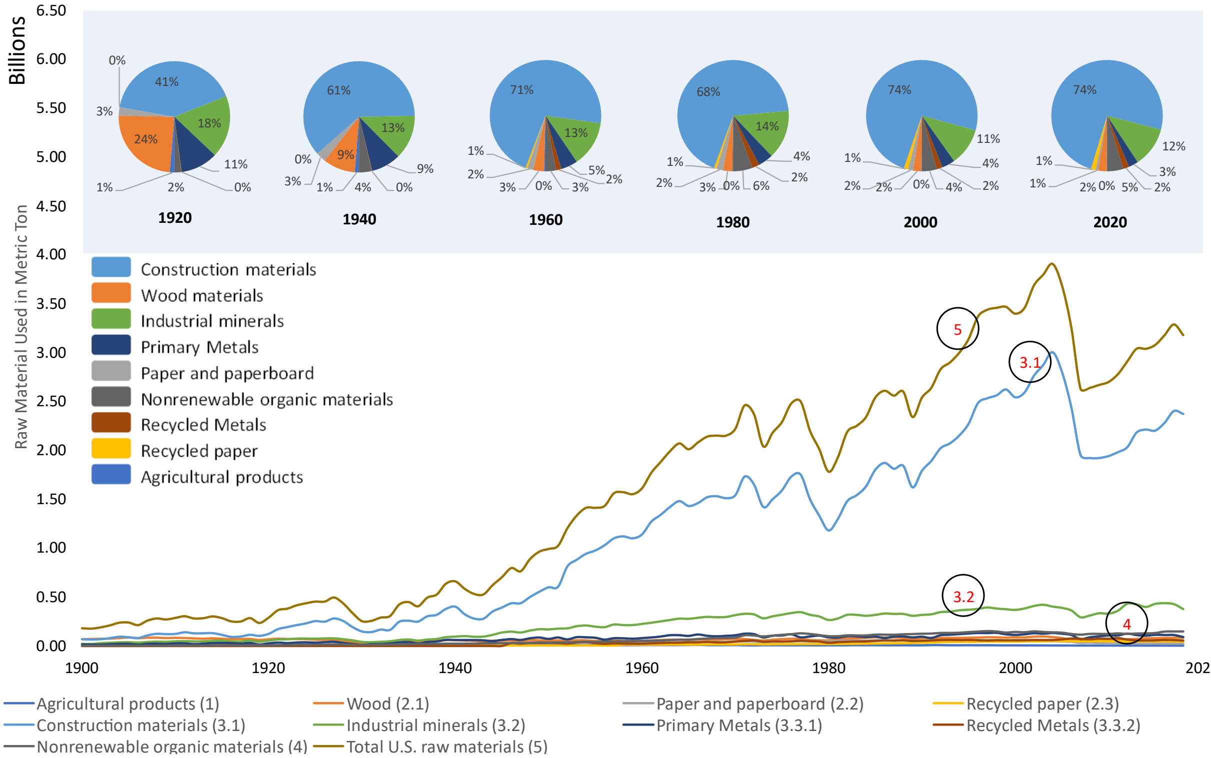


Figure 1: Raw material flows in United States in Gt/yr – highest contribution by construction materials (series 3.1) followed by industrial minerals (series 3.2). Series 5 shows total raw material in the US. Data source: US Geological Survey 2022

Globally, the material flows have climbed exponentially, from 28.6 Gt in 1972 to 101.4 Gt in 2021. In a business-as-usual scenario the flows are expected to jump to 170-184 Gt by the year 2050. The circularity score, defined as the proportion of secondary materials to total materials (raw, primary, and secondary) of the economy, has also fallen further to 7.2% which is the lowest since 2018 when it was first tracked [4], [5], [6]. This indicates that there is large untapped potential for global businesses to reduce waste. In the US, waste is classified in municipal solid waste (MSW), hazardous waste, and non-hazardous industrial waste (NHIW) categories. EPA reports that US generated about 265.3 Mt MSW and 14.61 Mt hazardous waste in 2018 [7], [8]. Resource Conservation and Recovery Act program at EPA manages 2.685 Gt of industrial solid and hazardous waste today [9].

1.2 Sustainability Goals and Circular Economy Efforts

Waste goal setting is challenging mainly because there is wide variation in the waste streams depending on the type of operations, especially in the manufacturing sector. Challenges faced by manufacturers for waste management are subjective and highly dependent on waste streams and type of operations. Hence, the identification of potential for improvement is not a trivial task. This makes it harder to get concrete estimates for potential improvement and therefore buy-in from management for a quantitative commitment. In spite of this, many organizations, due to pressure from investors and in vague view of benefits, do make commitments. Among Fortune 500 companies, 302 have made public commitments to UN SDG [10].

US Department of Energy's (DOE) Better Plants program has established Waste Reduction Network (WRN) for its partners to help them set and achieve waste reduction / CE goals [11]. Many of the participating organizations have set Diversion Rate (DR) Improvement, Zero Waste (ZW) / Zero Waste to Landfill (ZWTL) goals. Other distinct goals observed were CE in products, waste intensity reduction, and absolute waste reduction. Table 1 shows the percentage of participants with relevant type of goals.

In a different study of 400 companies, it was found that 75% of participants have sustainability goal commitments and 220 organization had waste reduction goals (WRGs). CE related goals were evident from 88 organizations, but 132 organizations had absolute, intensity based or recycled/recyclable inputs goals [12].

Table 1: WRGs for DOE’s WRN Partners

Goal Type	**% Participants**
Diversion Improvement	53.8%
Intensity / Normalized	30.8%
Circular Economy Transition	20.5%
Absolute Reduction	15.4%

1.3 Need for Accurate Performance Tracking Methods

Waste generation is a significant problem that requires innovative solutions in the industry. Due to variations in raw materials, processes, and equipment in industry, it is difficult to find a generic solution that will be effective for everyone. The first step in waste reduction for any organization is understanding the problem and commit to finding solutions by setting an achievable target. Prasetya et. al. in a study of small and medium enterprises (SME) found that increased knowledge of resource accounting and tracking can help these businesses tackle waste reduction problems and improve decision making [13]. The organizational performance and its production waste performance are deeply correlated [14].

The progress on the WRGs is demonstrated by accurate and reliable performance tracking methods. A key performance indicator (KPI) that is suitable for the process can highlight the course of action needed to improve performance substantially [15]. In other words, a KPI can help quantify the waste performance and help establish a baseline. But as shown by Marczewski for tracking waste performance with diversion rate standardized methods yield unstable results to track progress over time [16]. In addition, waste intensity as well as CE goals suffer from similar issues. Thus, it is imperative to scrutinize the available performance tracking methods for demonstrating progress. In the following sections we take a look at standard approaches to monitor waste performance, their pros and cons and suitability in some common manufacturing scenarios.

2 Methodology

In this qualitative paper, challenges encountered in tracking WRGs are studied. DOE’s Better Plants WRN has manufacturing partners that are actively working to reduce their waste. This network engagement was leveraged to gain better insights into partners WRGs. WRN is a technical assistance program to guide partners and create resources to help accelerate waste performance. Data on waste performance goals, how they are tracked which KPIs are followed was also collected from WRN partner interactions as well as through basic literature search. WRN partner interaction and critical literature review methodology was followed as highlighted in Figure 2.

A discussion of tracking of WRGs and performance calculation is presented in the results section. The paper looks critically at the goals and available tracking methodologies to evaluate situations in which difficulties may arise to demonstrate consistent improvement in the tracked KPIs or waste goal statistic. Further, the analysis provided is used to make recommendations on overcoming challenges to waste reduction performance calculation and tracking. Finally, a partner case study is provided that summarizes waste goal, difficulties faced during performance calculation and tracking, and solution to overcome the challenges faced.

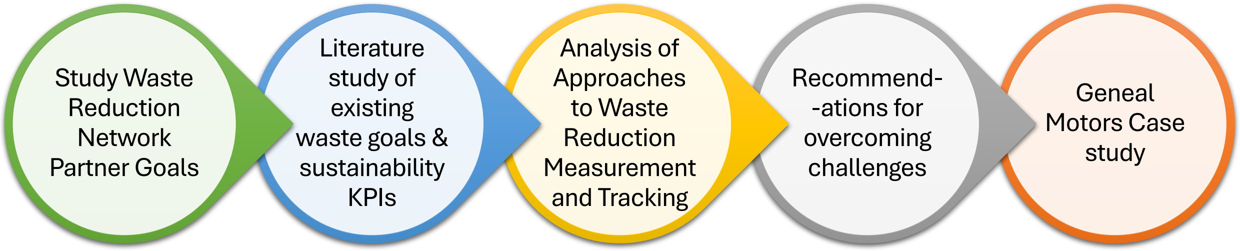


Figure 2: General qualitative methodology followed for research

3 Review of Approaches to Track Manufacturing Waste Performance

Waste is any unusable material produced as a direct or indirect result of production and related support operations. Waste reduction in manufacturing, therefore, refers to maximization of raw material use along with minimization of byproducts, quality rejects, refuse, and other supporting operations waste. These interpretations or their variations are used in literature and in practice to quantify waste from production processes.

3.1 Measurement & Performance Tracking

Accurate measurement of data sources is a corner stone for reliable quantification of waste quantities. Billed quantity records from haulers and invoices from waste management companies serve this purpose. Waste reduction tracking from this data is the process of monitoring and recording the data to track progress towards the waste performance goal. To enable waste reduction performance tracking accurate data, reliable quantification with suitable measurement is essential. Waste performance can be tracked by function, process, or equipment level or at a higher level of facility or organization wide level.

3.1.1 Facility, Enterprise-wide

Waste management and performance is usually referenced at a facility level or enterprise-wide level and requires an understanding of all on-site or enterprise-wide waste streams and their end-of-life destination [17]. Waste related measurements that are available to track waste generation and establish baseline as well as track progress are varied and can include categories such as overall generation quantities (mass, volume) or separated by waste streams, treatment methods, costs, etc. In many instances organizations normalize these measurements in order to benchmark performance and compare it with similar operations. The normalization factors commonly available to a business are based on production, revenue, personnel, etc.

3.1.2 Equipment, System, Process

Waste tracking and monitoring at the equipment or process level is not common in the industry and can be referred to as low level waste tracking on the shop floor [18]. With newer technologies such as Internet of Things and Radio Frequency Identification real-time tracking of waste performance as well as improvement is becoming easier to achieve. The analysis required is usually straight-forward.

3.2 Waste Related Goals and Tracking Approach

Waste measurements and equipment / process level KPI calculation form the basis for broader facility or enterprise wide waste program evaluation which can help an organization track its progress on waste related goal. Waste performance measurement at a program level can pose multitude of challenges. Tracking progress on a goal requires waste measurement at a granular level and rolling up the performance at the organizational level. Often it means that combining measurements from different facilities, processes, and systems to facilitate the analysis.

3.2.1 Diversion / Zero Waste to Landfill / Zero Waste Goals

DR and ZWTL goals focus on landfilled waste reduction and finding alternate pathways for waste streams that will prevent the waste going to landfill. EPA defines waste diversion as minimization of waste generation through source reduction, reuse, and recycling as well as composting organic waste instead of sending to landfills [19]. In addition to reducing landfill disposal costs, diversion can reduce environmental degradation by, preventing soil contamination, decreasing water table pollution, and reducing the need for incineration. ZWTL goal is also similar in objective. It eliminates / reduces directly discarded materials through source reduction or handling waste by means other than landfill as much as possible (usually ≥ 90%).

Zero Waste (ZW) on other hand is more complex, and has been defined in different ways by different states and city governments and organizations [20]. Zero Waste International Alliance (ZWIA) defines it as “the conservation of all resources by means of responsible production, consumption, reuse, and recovery of products, packaging, and materials without burning and with no discharges to land, water, or air that threaten the environment or human health” [21]. ZW is a state where there is no hazardous waste and no waste incineration or burning for energy recovery.

Some example goals in diversion include improving DR above certain level, e.g., Presidential EO14057 specifies that all federal agencies must improve their DR to 50% by 2025 and at least 75% by year 2030 [22]. In the manufacturing industry, many organizations have committed to >90% DR while others have committed to >50% DR. In some variations, manufacturers only commit certain number or percentage of facilities (90%, or 50%) to the DR target.

3.2.2 Normalized WRGs

Normalized or intensity based waste goals are found to be second most common goal type. Intensity basis recognizes the fact that the fundamental manufacturing process will have contribution to waste generation and if there are non-recyclable waste streams ZW may not be feasible with current technology. Waste intensity is usually calculated by dividing total waste generated with appropriate output metric such as production, revenue, labor hours, etc. Adoption of appropriate normalization factor is of paramount importance. The normalization represents direct correlation between basic waste generation activity and the normalization factor.

Some examples of the goal specification could be reduction in waste intensity over a period of time, e.g., 25% reduction in waste intensity over 5 years. The waste intensity improvement is tracked by recording periodic values. Comparison between baseline and current periods can show progress and distance from the anticipated goal.

3.2.3 Absolute WRGs

Absolute WRGs are straight forward as they just rely on simple measurement of total waste generation. Absolute WRGs can be helpful on an extremely large scale where no common metrics exist for normalization or there is no regular and reliable data collection on the normalization factors. With large variety of products and variable operations it may not be desirable to combine dissimilar measurements. It can be a result of organizations conducting exploratory analysis to figure out implementable projects and their estimated impact on waste.

Absolute waste reduction specification can be a goal in terms of reduction in mass or volume measurement or it could be a relative target that specifies a certain percentage of waste tonnage that should be reduced by a target date. The data are recorded periodically, and simple analysis is used to measure progress towards the goal.

3.2.4 Circular Economy Transition

CE transition goals are combinations of many initiatives. In addition to waste reduction, the transition signifies sustainability in the product, production, as well as business practices. Many manufacturers have taken a combination approach when adopting circularity goals, e.g., specifying circularity goals for certain product lines with a separate recyclability goal for packaging. Some other examples of CE transition goals include beneficial reuse rate of 80% or higher for waste materials, sustainable design criteria for all products, 90% products achieving more than 90% resource efficiency.

CE measurements address business model, raw materials and other resources used in manufacturing phase, product use phase, end-of-life treatment of the product, etc., i.e. full lifecycle assessment [23]. Therefore, it is a complex task to evaluate CE state of a facility or organization [24]. There are many frameworks proposed in literature with different approaches that try to measure the performance [25], [26]. Simplest of the approaches propose an index focused only on input and output materials. This can be applied at a product, facility, or organization level to calculate performance. On other hand, Ellen McArthur Foundation has developed Circulytics 2.0 which is a comprehensive approach to measure circularity performance of an organization [27].

3.3 Key Performance Indicators Tracking

KPIs are vital measurements that help quantify current performance and helps management plan for further course of action [15]. KPIs are widely used in manufacturing as well as other industries and can be instrumental in improving performance. However, selection of appropriate KPIs is the crucial task. Kibira et. al. developed and demonstrated a method for selection of sustainable manufacturing KPIs [28]. A KPI can be directly tied to a measurement e.g., tolerance based quality rejects produced per hour for a precision aviation component, or it could be normalized based on factors, e.g., number of machines running. A ratio of the two will result in a KPI –

$$\text{Tolerance rejects per machine} = \frac{\text{Number of rejects per hour} \mid \text{tolerance}}{\text{Number of running machines}}$$

Creation of appropriate ratio indicators can be helpful to quantify waste performance at an equipment, system, or process level. Examples of Waste reduction KPIs that are used in metal fabrication and related manufacturing include – scrap rate, trim ratio, rework rate, material efficiency, etc. Process and equipment that results in scrap can benefit by using scrap ratio as an indicator of the performance. If the process capability is low for a particular component design, it may result in a higher percentage of components that need to be reworked. The rework rate can provide insight into equipment settings, process or design parameters which can be adjusted based on the rework rate calculation. Trim ratio can be employed to maximize material usage by optimizing the cuts. The waste cost ratio provides a lagging indicator of the total waste produced for a unit, product or the facility for the upper management. The cost related information even though not useful at the shopfloor may be helpful to trigger management action.

CE transition is becoming rapidly a prevalent goal for leading manufacturers. KPIs designed to help indicate status of the transition have been proposed in literature. Reuse Rate is an example of a KPI that can help track progress towards increasing reuse of waste material in the production process. Saidani et. al. reviewed 55 CE Indicators from literature and designed a decision support tool to select indicators that fit manufacturing circumstances [29]. There has been significant consideration given to sustainability indicators of CE in literature, which can help gauge sustainability performance prior to implementation [28], [30].

4 Suitability Evaluation of WRG Metrics

With critical consideration of the WRG goals found in literature and those practiced in industry, distinct advantages and disadvantages are evaluated. As a result of the research, this section puts forth pros and cons of different types of WRGs, as well as limitations encountered.

4.1 Pros and Cons of Approaches

There are many ways to define WRGs depending on the long term vision and details of production operations that align with strategic goals of the manufacturers. The higher level of facility or organization-wide goals and tracking can feed from equipment, system, or process level KPI tracking. There are certainly eventualities for each goal and KPI which will act as advantages and disadvantages for each type of goals or KPI.

The advantages for DR goals include its wide acceptability in the industry and hence the ability to act as the single metric to report on. As it is a single metric for the organizations that have more than one facility and wish to roll up their performance numbers from single unit up to corporate performance can easily do so using DR. It also enables benchmarking with leaders in the industry and can signify compliance with city and municipal guidelines for businesses. As there is not a clear nationally or internationally agreed upon definition of DR, possibility exists for errors and misinterpretation in calculations at individual process units and facilities. Local and state laws differ on various waste streams, their acceptable treatment options or shipping & transport regulations for access of treatment providers. This can make it difficult for organizations to adopt a uniform strategy for waste streams across all operations and may introduce additional costs.

Absolute WRGs are easy to record, roll-up and track which is their biggest advantage. On a facility level the measurements are readily available through the waste haulers and treatment invoices. The data availability and reliability are usually high. The tracking is easy to interpret and provide a clear understanding of the level of effort necessary to achieve the goal. However, the most common disadvantage of these goals is they do not provide a consistent way of comparing performance within facilities or process units which can be a crucial input for capital allocation. Many businesses see production growth as their primary driver which is deeply correlated to waste generation. This means that if there is variability in production in lower production years the waste reduction will automatically be higher. Conversely, the absolute WRGs are a harder target for high growth manufacturers. Other major disadvantages include tracking dissimilar waste streams among compared facilities, variable units for tracking volume or mass or unit systems followed by waste haulers, e.g., short tons vs thousand gallons.

Normalized waste goals tie the most relevant variable responsible for waste generation activities as a normalizing factor to total waste generation. A waste intensity is a form of normalized waste statistic tied to production or revenue. The waste goals are standardized and somewhat scalable, i.e., account for variation in waste generation in direct proportion to production. Normalized goals offer best capability to benchmark across facilities, process units, and within similar industry segments. Robust data usually produces stable normalized statistics which is great for tracking purposes. Normalized goals are somewhat complex goals to keep track of as there are more variables to measure. The data burden is higher along with analysis and interpretation. The stability is highly dependent on the normalization factor along with robustness. Sometimes if there are 'efficiencies of scale' involved the indicated progress may not represent actual progress. Normalized tracking assumes that normalizing factor is directly proportional with waste generation and at zero value the waste generation will be zero, which may not always hold true except for in certain specific cases. Accuracy is dependent on how close the normalization factor is to actual production activity.

CE transition goals are most sought after in manufacturers that are trying to reduce their environmental footprint aggressively. A CE transition goal signifies long term commitment to sustainability and can improve brand value as well the financial performance through efficiency and ESG metrics. The advantage of the goal includes sustainable waste reduction with life cycle thinking. Moreover, the most significant upside for manufacturers with CE goals is the decoupling of material extraction and value creation. Literature sources show significant bottom line improvement with 9R strategies such as remanufacturing and beneficial reuse [31]. The advantages go beyond implementing manufacturer and extend to supplier network. CE transition goals are the most complex to evaluate. The 9R framework covers the entire life cycle of the product and therefore the transition means alteration of even the most foundational principles such as the business model. The evaluation frameworks can be complex and almost certainly involve help from a third party to track the progress towards goal. The data burden is the highest in the CE transition goals and for a typical manufacturer many sources will need to be newly incorporated in order to establish a baseline and then track progress. The calculation is dependent on how the organization defines its policy on CE transition, therefore the scoring is subjective to individual goals. Table 2 details waste reduction goal metrics, the evaluation method and usual tracking method that denoted average improvement over periods and total improvement.

4.2 Other Challenges and Limitations to Waste Reduction Progress

WRGs on their own exhibit disadvantages as discussed previously. Well thought out goals with clear policy and consistent indicator metrics can make tracking progress easier. However, while tracking progress is beneficial certain limitations do arise. The goals track specified metrics which do not provide understanding of causal information and do not allow for deeper analysis with the exception of CE transition goals.

Table 2: Waste Goals Evaluation and Periodic Tracking

Metric	**Evaluation**†	**Periodic Improvement Tracking**†
Diversion Rate (DR)	$TD = TW - TLF$ $TD = SR + TRU + TRC + TCo + TER$ $DR = \frac{TD}{TW}$ $DR = 1 - \frac{TLF}{TW}$	$AI,\% = \frac{(DR_C - DR_B)}{P_C - P_B}$ $TI,\% = DR_C - DR_B$
Normalized Waste Intensity (WI)	$WI = \frac{TW}{OP}$	$WII = WI_B - WI_C$ $AI,\% = \frac{WI_B - WI_C}{WI_B} \times \frac{1}{(P_C - P_B)}$ $TI,\% = \frac{WI_B - WI_C}{WI_B}$
Absolute Waste Reduction (AWR)	$AWR = TW_B - TW_C$	$AI,\% = \frac{TW_B - TW_C}{TW_B} \times \frac{1}{(P_C - P_B)}$ $TI,\% = \frac{TW_B - TW_C}{TW_B}$

† Nomenclature: TD = total diverted waste, TW = total waste, TLF = total landfilled waste, SR = waste reduced through source reduction, TRU = total reused, TRC = total recycled, TCo = total composted, TER = total waste energy recovered, OP = output metric, AI% = average improvement%, TI = total improvement%, P = period, WII = waste intensity improvement.
Subscripts – B = baseline, C = current

While tracking DR and ZWTL, information is collected about waste streams and total waste produced including how much waste went to landfill and how much waste was eliminated from landfill due to source reduction or recycling. Thus, the goal tracking focuses on the end result of DR but loses the information about hierarchy of waste disposal, i.e., how much waste could have been prevented instead of being recycled. Instead, DR is a metric that equalizes prevention with recycling by assigning them the same improvement benefit. This loss of information can be a hurdle for real progress in the battle for waste reduction. In addition, there are varying definitions of ZW and ZWTL which can impose varying standards on material and energy recovery from waste.

It should also be noted that WRG tracking does not address the systemic challenges to waste reduction. No waste goal tracking method provides a framework to account for lower recycling rates due to contamination in waste streams. Contamination of waste streams has been found to be a serious issue for recyclers which can reduce the financial incentive of recycling or lead to ineffective recycling. Access to support from supplier networks cannot be accounted for by using the tracking methods. Other systemic issues that can affect waste reduction performance but cannot be accounted for in the goals tracking include –

- Limited infrastructure availability, e.g., material recovery facilities
- Unavailability of skilled talent for CE transitions, i.e., redesigning of product, material substitutions, etc.
- Higher level support to create new industrial ecologies for reuse, repurpose, and waste-to-resource strategies

5 Discussion on Overcoming Challenges to Track Waste Goals

Waste generation is highly sensitive to operational efficiency and waste streams can vary widely depending on manufacturing process. As discussed, waste goals and designed KPI tracking can generate necessary insights from data that can be used to better guide efforts in waste reduction. KPIs such as scrape rate, rework rate, trim ratio, reuse rate, etc. as discussed in earlier section, are well suited for metal working and fabrication industry and can guide where the process is most waste intensive. For an organization in the Food and Beverage industry these KPIs will not work and need to be redesigned so that specific information about process waste could be highlighted. In cast iron foundry industry, the major waste products include spent foundry sand, slag, and cupola dust which can all be recycled and hence a diversion or beneficial reuse for foundry sand can be a good fit and can be tracked. The results can help quantify effectiveness of the waste performance.

The strategies adopted to treat waste can make a significant difference in demonstrating waste performance. For example, for a manufacturer that favors recycling strategy and has a large waste stream of used contaminated plastics and thin plastic films (cosmetics industry) it will be difficult to achieve ZWTL or high DR goal. In contrast, packaging redesign, material lightweighting, etc., CE transition strategies will work well. The policy on the waste treatment hierarchy can make a significant difference as well. This is because waste streams like plastics, used tires, and food waste have high energy content and can be easily diverted from landfills for energy recovery.

Periodic tracking of DR is straight forward provided the organization clearly defines the acceptable end-of-life options that can be employed as diversion strategies in accordance with organization policy. This will reduce effort in interpretation of the policy, make finding available strategies easier, reduce errors due to assumptions, and provide comparable waste statistic across the organization. If allowed exceptions are standardized to adjust for local and state laws, it will further streamline calculations and improve reliability and robustness.

Absolute WRG can be a good startup strategy for a newer waste reduction program to gauge potential of alternative strategies available for specific waste streams. To overcome some of disadvantages of absolute goals, targets may be set for specific waste streams, e.g., plastic packaging waste, adopt standard unit system as well as weight to volume ratios for all encountered waste streams.

Normalized goals are well suited for waste reduction programs that have more mature data collection programs and can ensure availability, reliability, and continuity of the data. In the event there are more than one equally important factors that affect waste generation and the assumption of ZW generation at zero production level cannot be satisfied, a regression based approach could be adopted to track actual improvement in waste reduction. Normalization factors can be selected based on a decision criteria such as the highest correlation coefficient among available measurements. The remedies can mitigate errors and disadvantages encountered when dealing normalized waste goals.

CE transition goals can be very unclear and therefore policy details on different 9R initiatives, that can be considered can help solidify the commitment. The goal established can specify the methodology followed to evaluate the CE transition score which can help interpretation of the initiatives and options for investigation of CE adoption. CE approach is standardized by measurement frameworks such as the ESRS E5, ASTM E60, Circulytics 2.0 among many other proprietary software systems for metrics. This can create a uniform assessment of circularity and benchmark operations that could be compared globally.

6 Case Study

To encourage sustainability within the U.S. manufacturing sector, the U.S. Department of Energy (DOE) developed the Better Buildings Better Plants (BP) program. Through this program, the DOE has partnered with leaders in industry to improve energy efficiency and sustainability in manufacturing. As a global leader in the automotive industry, General Motors (GM), was a founding partner of the BP program. In collaboration with the program, GM has implemented a variety of sustainability initiatives to reduce their waste, energy, water, and carbon impacts.

6.1 Waste Reduction Goal

GM has an active waste minimization program and achieved their first landfill-free facility in 2005. Then pursuing more formalized goals thereafter, GM has invested significant effort in waste reduction. GM established a “Zero Waste” sustainability goal in 2019 with which it aims to divert >90% of operational waste from landfills, incinerators, and energy recovery facilities by 2025. GM’s waste management program adopted the Zero Waste International Alliance’s (ZWIA) definition of zero waste and is based on the ZWIA's standard diversion threshold of 90% [20], [21].

6.2 Challenges in Waste Tracking and Methodology for Diversion Calculation

With the creation of their Zero Waste Program, GM adopted a new methodology to track their diversion rate in order to measure progress towards their new WRG. Under the previous landfill-free program, GM utilized an instantaneous DR calculation, measuring the ratio of total amount of waste diverted from landfills compared to the total waste generated in a specific time frame. However, this DR suffered from instability as both generated waste and waste avoided from landfill varied from period to period due to fluctuations in production. GM determined that the metric presented a simple snapshot of waste performance and did not fully address the long-term performance goals [16].

Therefore, GM began the process towards establishing a new tracking methodology to meet the program needs and allowed for more granular data collection and visualization. The GM team evaluated DR methodologies from Underwriter Laboratories Solutions standard UL2799 which allows incineration with energy recovery as a viable option for diversion, but excludes incineration without energy recovery [32]. The team also evaluated Green Business Certifications, Inc. (GBCI) standard Total Resource Use and Efficiency (TRUE) DR that does not allow incineration as a valid landfill diversion path [33]. However, upon review, GM determined that both methodologies can indicate lower waste diversion when diverted materials are reduced year-over-year and can't be accurately tracked without documentation, such as a waste manifest. These methodologies did not align with GM's waste hierarchy, which has source reduction as the most effective management method, therefore, utilizing these calculations could mislead stakeholders that the program was not effective [16].

GM developed a strategy to solve for these difficulties. During the program redesign, a three-step strategic planning process was followed – define a new tracking methodology, establish long term and interim goals for the entire organization, including plant and regional targets, and development of the implementation plan [34]. The team reconsidered the program, acceptable waste treatment pathways (Figure 3) and DR calculations. GM based its new zero waste hierarchy on best practices from ZWIA's Zero Waste Hierarchy. In addition, GM's updated diversion methodology was designed to track performance over time using an approach based upon the revised edition of the Greenhouse Gas Protocol when tracking emissions. The key difference from the earlier calculation was to move from an instantaneous rate to a baseline calculation, which compares current year non-diverted waste against a baseline period. The new DR is,

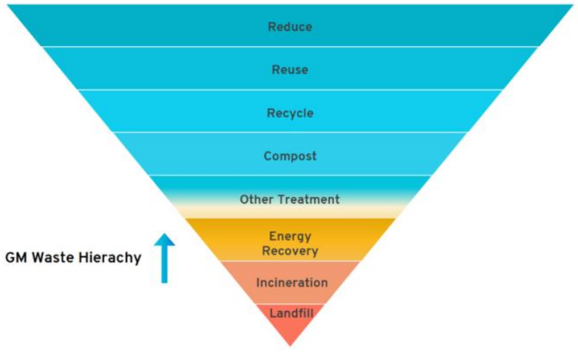


Figure 3: GM's Zero Waste Hierarchy Definition

$$DR_{New} = 1 - \frac{\sum m_{non-diverted} - \sum m_{exempt,non-diverted}}{\sum m_{Baseline} - \sum m_{exempt}}$$

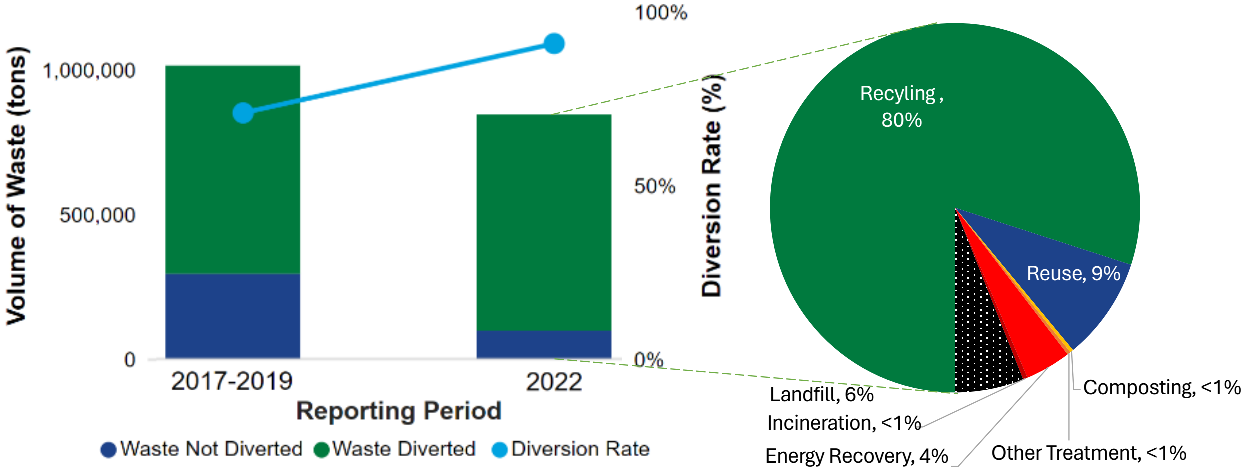
The mass (m_{exempt}) of the exempt waste includes the waste generated in non-operational activities such as construction, demolition or remediation projects. The advantages of this new method were threefold: (i) It offered a measurable metric that could indicate progress of the waste diversion program compared to a baseline, (ii) It created a metric that offered stable results, (iii) and most importantly, it aligns with GM's Zero Waste goals and ambitions to prioritize moving waste up GM's Zero Waste Hierarchy [34].

This newly designed metric for DR allowed for better target tracking, but GM also sought to improve operational strategies to reduce waste. Revising operational strategies involved 4 key steps: Creation of a dedicated ZW Budget, forming ZW working teams, designing and implementing data compilation and calculation tools, and a systematic approach to ZW projects (approval, implementation, and scaling). To assist with the program's success, a variety of resources and tools were implemented [34] –

- ZW Treasure Hunts – A cross-functional team of SME's that take a hands-on approach at the facility level to collaborate with site personnel to identify opportunities and perceived challenges
- ZW Mini Missions – Focus groups to investigate diversion opportunities for high impact waste streams
- Partnerships – Established 3rd party partnerships to accelerate large scale waste reduction and innovation projects
- Budget Prioritization – Deployed standard ZW business case tools to evaluate and prioritize diversion projects
- Strategic planning and Implementation – Cost and risk analysis of projects and implementation

6.3 Success

During the baseline years (2017-2019) GM facilities in the United States generated an average of 1,014,602 tons of operational waste and diverted 719,505 tons of that total, achieving a DR of 71%. By complementing enhanced performance tracking with operational improvements, GM improved their waste management program substantially. In their 2022 sustainability report, GM announced that they reached their target DR > 90% 3 years ahead of schedule, producing 848,110 tons of operational waste in their US facilities and diverting 746,788 tons of that total, achieving a DR of over 90%. GM will be officially recognized by DOE for their waste reduction performance in Better Plants Waste Reduction Network. GM is now working internally to build on their existing program and establish their next public zero waste goal and time frame.



(a) (b)

Figure 4: GM's waste performance from baseline to goal achievement (Source: (a) DOE's Better Buildings Solution Center, (b) GM 2022 Sustainability Report)

7 Conclusions & Recommendations

With the new era of open Environmental, Social, and Governance (ESG) reporting many manufacturers are trying to track waste with higher reliability. Since waste reduction is such a diverse field there are many approaches to establish improvement goals that align with organization's philosophy. The problem often encountered is that of non-standard definitions of the terms ZW, CE, DR. Overall, the presented work looked at WRGs set by manufacturers and reviewed existing approaches to track organization performance. The challenges faced by manufacturers in tracking progress are varied. A general solution to the tracking problem that accounts for differing waste streams, measurements, and desirable metrics is difficult.

WRGs are mainly specified in four different forms – (i) DR improvement, (ii) normalized waste intensity reduction, (iii) absolute waste reduction, and (iv) CE transition. Depending on the scope of the goals, the waste performance should be tracked on the facility, a major process, or system level. The paper established advantages and disadvantages of each of the goal types. Sustainability managers can leverage these considerations to shape the corporate waste programs. To launch or revise corporate waste goals, a comprehensive evaluation of available measurements versus needed data and effect of adoptable waste management strategies on desired metrics is necessary as discussed and demonstrated in this research.

Process, system, and equipment level KPI tracking can fine tune waste reduction performance tracking and can generate insights necessary to guide management focus on future projects to reduce waste. For waste goals to be successful, the defined metrics need to be consistent, clear, and communicated regularly. A well-defined policy on acceptable waste treatment pathways will be the backbone that drives a waste reduction program.

Finally, the paper looked at the case of General Motors ZW program through which GM aimed to improve DR to >90% across their operating footprint in the United States. GM realized shortcomings of the previously utilized DR metric and modified it to reflect measurable progress of waste performance against a baseline. Through this tracking and improved focus on the ZW program, GM achieved its diversion goal 3 years ahead of the target. This shows the importance of designing waste reduction metrics to track progress along with a focused effort on improvement.

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About the Author(s)

Subodh Chaudhari is currently an Associate R&D Staff Member at Oak Ridge National Laboratory (ORNL). He has more than 14 years of experience in industrial energy efficiency and waste minimization assessments. He leads resource development in DOE’s Waste Reduction Network of the Better Plants Program. He achieved his Master of Industrial Engineering degree from West Virginia University.

Alexandra Botts is currently an Assistant R&D Staff Member at ORNL. She is a Technical Account Manager in the Better Plants Program. She has more than 4 years of experience in energy assessments, treasure hunts and is a compressed air efficiency expert. She earned her Master of Industrial Engineering degree from West Virginia University.

Dr. Sachin Nimbalkar is the group leader of ORNL’s Manufacturing Energy Efficiency Research and Analysis Group. Dr. Nimbalkar has more than 15 years of experience in process heating systems and energy efficiency research. He received his PhD and master’s degrees in mechanical engineering from Rutgers University.

Cory Tatarzyn is the Global Zero Waste Program Manager at General Motors. He has more than 6 years of experience in sustainability and environmental engineering. He obtained his Bachelor of Environmental and Ecological Engineering degree from Purdue University.

Tina Burry is the Manager for Circular Economy at General Motors. She has more than 25 years of experience in engineering and sustainability area. She earned her Bachelor of Geology and Earth Science at Michigan State University.

Thomas Wenning is currently Better Plants program manager and senior R&D staff at ORNL. He has more than 15 years of experience in industrial efficiency and decarbonization. He obtained his Master’s degree in mechanical engineering from University of Dayton.