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EDITORIAL

Toward dynamic sustainability assessment in the digital age

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The United Nations' Sustainable Development Goals (SDGs) were set up in 2015 and are intended to be achieved by 2030. Those highly interlinked goals reflect a need for the balanced development of economic, environmental, and social sustainability. Among numerous ways for goal achievement, industrial sustainability has been playing a profound role. It is increasingly shown that companies making sustainability as a goal are achieving competitive advantage. Industrial sustainability is commonly pursued through catalyzing, planning, and delivering changes through a hopefully optimal transformation path toward a preset goal (Tonelli et al. 2013; Moradi Aliabadi and Huang 2016a). In the process, an industrial organization needs to determine what current sustainability status and trend are, what it should sustain, what bottlenecks and challenges are, how to sustain optimally, and how effective strategies and actions could be, among which sustainability assessment is the first, critical step.

Sustainability assessment is known as a process of identifying, measuring, and analyzing a system's performance, and evaluating the potential impacts of technologies and other solution alternatives on performance improvement. Over the past two decades, numerous types of sustainability metrics systems have been introduced, where indicators are defined in a combined process using a normative top-down approach or a problem-related bottom-up approach (Halla and Binder 2020). While the former is an operationalization process, starting from identification of constitutive elements of sustainability, through determination of sustainability goals, application of sustainability principles, to indicator development, the latter is a contextualization process, where indicators are generated based on the specific problems/questions of a system of interest. As sustainability is triple-bottom-line-based, every metrics system contains three sets of indicators for assessing economic, environmental, and social sustainability separately. This has posed a challenge about the aggregation of the information provided by individual indicators in each sustainability dimension as well as the overall sustainability covering all three dimensions. The aggregation leads to creation of composite sustainability performance indices. Sikdar and co-workers stated that it is deemed desirable to consolidate all usable indicators into one aggregate metric to make performance comparison easier (Sikdar et al. 2012). Common aggregation methods include simple mean (i.e., arithmetic average), weighted mean, and (weighted) geometric mean. However, there is no scientific method to uniquely determine weights. In practice, the weights are commonly selected based on survey of preferences of informed individuals and value judgment. The other challenge is about data availability and quality, which affects the selection of indicators and could influence the comprehensiveness and preciseness of sustainability assessment (Diwekar et al. 2021; Moradi Aliabadi and Huang 2016b). It is possible that if a large amount of real time, quality data are accessible, sustainability performance could be evaluated more frequently, broadly, and reliably.

Today, industries are in the midst of significant, compelling transformation regarding technology innovation and the ways products are manufactured. This is largely impacted by Industry 4.0, which is mainly featured by digitalization. New and relatively low-cost technologies for smart sensing and operation, fast data communication among sensor node, database, internet, and cloud services in manufacturing sites start to be used. These provide a variety of opportunities for advancing engineering sustainability research and practice. Among top strategic digital technologies, the Digital Twin (DT) technology receives significant attention (Jones et al. 2020). A DT is a virtual representation that serves as a digital counterpart of a physical system, which could be an object, a product, a process, a plant, or beyond. It can be developed using any sort of models (physics-based or data driven), as long as it can sufficiently and accurately represent a physical system, whose behavior may change over time. Thus, a DT is characterized by real-time reflection, interaction, and convergence in physical space, between

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historical data and real-time data, and between physical and virtual spaces, and self-evolution. For a large or complicated system, a set of DT's may be necessary, and the connected DT's can generate a variety of real-time data to help manufacturers better understand and analyze the system, and predict problems in advance, give early warnings, prevent downtime, develop new opportunities and even plans for improving system performance. The widespread reach and usage of the Internet of Things (IoT) have made DT more cost-effective and accessible for the manufacturing world.

As the DT technology starts to play a fundamental role in creating a data-rich virtual environment in industry, it should be also highly valuable for the investigation of industrial sustainability problems, as it allows to quickly assess the information of both existing and planned production mixes and to compare achievable impacts with changing processes, products, and technologies, thus enabling advisory features for decision making in a structured way. DT is being exploited in the assessment of sustainability performance of products. But almost exclusively, the known works are about general views and discussions, with very narrow concerns on some specific energy or environmental problems in product design (Carvalho and da Silva 2021). Hitherto, no report on systematic, comprehensive methods for DT-based sustainability assessment and decision making has been identified.

In industry, sustainability assessment is commonly conducted annually and improvement strategies are developed accordingly. This is reflected in numerous annual sustainability reports of large manufacturing companies, which are publicly accessible. It has been questioned more frequently whether sustainability problems could be comprehensively identified, assessed, analyzed and predicted in time so that solutions could be derived and actions be taken quickly. From the sustainability science point of view, this is a dynamic sustainability problem that may involve continuous learning and problem solving, ongoing adaptation of strategies with a primary focus on timely improvement as opposed to delayed actions. The first and most critical step of dynamic sustainability is dynamic sustainability assessment.

There are a number of fundamental questions for dynamic sustainability assessment, such as how often sustainability assessment should be conducted, should traditional sustainability metrics be updated and whether should any new metrics be introduced, how to conduct dynamic sustainability assessment, and how to evaluate real benefits gained from it. It is envisioned that digital twinning will play a unique role in responding to these questions. For a variety of manufacturing systems, the first-principles-based and/or data-driven neural network-based or statistical models are all adequate for being a key component of a DT, and the model parameters can be adjusted over time as new real-time data are continuously acquired. A set of DT's can be used to construct a virtual plant. Such a virtual plant should be highly valuable for the following tasks in dynamic sustainability assessment. First, it can generate time-series data necessary for evaluating energy and material efficiency, water use and reuse, product/intermediate product quality, waste generation, process safety, etc. A subset of sustainability metrics system can be selected to assess system performance in a number of focused areas for a period of time as appropriate. Second, it is possibly more important that the DT-based virtual plant generates some sustainability-relevant new information that may not be measurable in a physical plant. Third, the virtual plant can be used to conduct simulation for the manufacturing activities in different scenarios reflecting market and supply chain uncertainty, new environmental regulations, etc. This could make the sustainability performance of a system dynamically predicable. Fourth, a virtual plant could serve as a test bed for testing, at nearly no cost, a number of technology alternatives for their capacity of sustainability performance improvement, based on the dynamic sustainability assessment results. Furthermore, the DT technology could also contribute to the determination of weighting factors associated with individual sustainability indicators in a holistic way.

In the digital age, the manufacturing industry is shifting toward fast implementation, just-in-time model-based manufacturing, and frequent product transitions, and manufacturing activities become more intelligent. The data-rich environment, particularly with ample real-time data accessible, offers the best opportunity for developing a knowledge base that contains key information revealing intrinsic relationships between a system's dynamic behavior and sustainability performance change. It is conceivable that dynamic sustainability assessment will receive increasing attention, and many methodological studies that address those fundamental issues, with successful industrial applications will be reported soon.

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