A Methodology to Model the Integrated Nature of the Sustainable Development Goals: Importance for Engineering Education

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Abstract
There are 17 Sustainable Development Goals (SDGs), comprised of 169 targets and measured by 230 indicators, that cover a myriad of development areas including food, water, sanitation, energy, governance, and climate change, and more. Engineers interested in contributing to the SDGs must be able to understand not only each goal in depth but also their integrated nature. This paper first emphasizes the importance of: (i) incorporating the SDGs in engineering education; (ii) making engineers aware of their contribution to the SDGs; and (iii) encouraging engineers to embrace a new systems-thinking mindset to address the SDGs in an integrated manner. The second part of this paper proposes an engineering analytical cross-impact analysis approach to quantify the interactions among the SDGs and organize and prioritize the goals that could most impact the others. Our analysis shows that focusing on SDGs 04 (Education), 06 (Water, Sanitation, and Hygiene), 07 (Energy), 11 (Cities), but especially 12 (Consumption), 16 (Governance), and 17 (Partnerships), will influence the other goals and aid in their success. It was also found that focusing on eliminating poverty (SDG 01), counter-intuitively, worsens poverty, since it inhibits the other goals on which poverty depends on.

Keywords: SDGs, Sustainable Development Goals, systems thinking, cross-cutting, cross impact, engineering education, epistemic network, methodology
Introduction

The United Nation’s (UNs) 17 Sustainable Development Goals (SDGs), shown in Figure 1, consist of 169 targets and 230 indicators. As described in the resolution adopted by the General Assembly on 25 September 2015, the aim of the SDG framework is to cultivate and expand humanity’s desire to “do good” while also organizing its ability to do so. The SDGs “… seek to build on the [previous] Millennium Development Goals and complete what they did not achieve (United Nations General Assembly 2015).” In launching the SDGs in 2015, the General Assembly of the United Nations “recognize[s] that eradicating poverty in all its forms and dimensions (including extreme poverty) is the greatest global challenge and an indispensable requirement for sustainable development (United Nations General Assembly 2015).” To that end, the SDGs represent “a plan of action for people, planet, and prosperity,” which in addition to peace and partnership, define the five “P’s” of the mission of the SDGs. To accomplish that mission, there needs to be a “balance [between] the three dimensions of sustainable development: the economic, social, and environmental (United Nations General Assembly 2015).” It must be acknowledged that fulfilling the mission of sustainable development is indeed a daunting task, a truly formidable undertaking, unparalleled in human history.

It should be noted that even though there are many goals and targets, eradicating extreme poverty (SDG 01) is the ultimate goal, but only if it is accomplished in an environmentally benign way. The other goals can be understood as constraints and requirements that the goal of eradicating extreme poverty must also satisfy.

Figure 1. The 17 Sustainable Development Goals (Global Goals 2016)
Engineers have had a limited role in formulating the SDGs and their predecessors, the Millennium Development Goals (MDGs), even less. This is unfortunate because for the goals and their targets to be met and solutions to various development issues proposed, technical and non-technical factors that underlie each SDG need to be understood in a qualitative and quantitative way. Target 7 under SDG 04 aims to “ensure that all learners acquire the knowledge and skills needed to promote sustainable development,” which fundamentally requires the involvement of engineers and therefore engineering education (United Nations Economic and Social Council 2016). The American Society of Civil Engineers (ASCE 2015) recommends that engineering graduates need to have a deeper knowledge and understanding of sustainable development in their overall university education with a special focus on the social aspects of sustainable development. Promoting and integrating sustainable development in engineering education is therefore necessary to accomplish the SDGs within the desired timescales.

Engineers need to approach the SDGs in an integrated manner and consider their interconnections when developing solutions to global development problems. As noted at the 70th session of the General Assembly of the United Nations, “[t]he interlinkages and integrated nature of the Sustainable Development Goals are of crucial importance in ensuring that the purpose of the new Agenda is realized. If we realize our ambitions across the full extent of the Agenda, the lives of all will be profoundly improved and our world will be transformed for the better (United Nations General Assembly 2015).” The work presented herein uses an integrated (i.e., systems) approach to understand the linkages that exist between the SDGs and their targets. Formulating these linkages and presenting them in a manner that can be understood by decision makers is of paramount importance to those, engineering notwithstanding, who will be involved in addressing the SDGs over the next 15 years. We present below a methodology for doing so, as we see the SDGs and their targets not as individual entities but as being intra-connected (at the level of each goal), inter-connected (across goals), and being dynamic pieces of a larger sustainable development framework. To successfully implement and accomplish the SDGs, it is therefore necessary for all SDG-interested parties to adopt an integrated approach and a systems-thinking mindset.

Even though the creators of the SDGs recognized the need for understanding their intra- and inter-connections, limited research has been done to qualify and quantify them. For instance, the interest in the development literature since 2011 for understanding the food-energy-water (FEW) nexus (World Economic Forum 2011) requires looking at the interaction between SDGs 02, 06, and 07 dealing with food, energy, and water security, respectively (Weitz et al. 2014). SDG 15 must also be included when considering the water-energy-land-food (WELF) nexus (Mohtar 2016). Despite the importance of the nexus in human development, existing models of the FEW/WELF nexus have remained qualitative and fall short of quantifying the interactions at play among the water, energy, food, and land sectors.

Being able to account for the intra- and inter-connections of the SDGs has potential to produce a higher level of understanding in sustainable development. One such example related to health is about understanding why people are getting sick? Is the environment polluted? Do people lack transportation to reach a clinic? Is corruption making the healthcare system
ineffective? Are people getting sick or injured from lack of nutrition? The actual answer is likely to encompass parts of the answers to all these related questions. Many other questions need to be asked and research must be carried out before a solution could be found. Furthermore, focusing on one solution over another could worsen the overall situation. If the problem is primarily pollution from poor environmental condition, then focusing on improved transportation for healthcare could make pollution worse. Additionally, improving health care could lead to unintended consequences to other areas. For instance, if improving health hurts food security because of the increased quantity of food needed in a community, then the net good among health and food security could be negative. This dynamic is but one small piece of the complexity that is inherent in sustainable development. It also emphasizes why systems thinking should be part of the body of knowledge necessary for engineers to address one or several components of the SDGs and sustainable development in general. Simply put, the SDGs cannot be approached in a linear and deterministic way.

**SDGs and the Grand Challenges of Engineering**

Since the Rio Summit in 1992 and the publication of Agenda 21 (UNCED 1992), the engineering profession has explored ways to contribute to sustainability and sustainable development (Roberts 2002). The engineering profession did not, however, contribute much to the agenda of the MDGs from 2000-2015. The SDGs provide a new and unique opportunity for the engineering profession to develop comprehensive technical guidelines to define the goals, their targets, and indicators better. More specifically, civil engineers have a unique role to play in defining better SDG 02 (Food Security), SDG 06 (Water, Sanitation, and Hygiene), SDG 07 (Energy), SDG 09 (Infrastructure), and SDG 11 (Cities), and to contribute, to a lesser extent, in addressing the other eight goals. It should be noted that civil engineers already deal with complicated systems (for which we know the unknowns but experts are required). In order to address sustainable development, they need to acquire a complementary systems-thinking mindset to deal with more complex systems (for which we don’t know the unknowns) and their interactions (Snowden and Boone 2007). All fields of engineering (not just civil engineering) have expertise to offer to address the SDGs, and disciplines related to one or several aspects of global development (e.g., engineering, political science, social science, etc.) must be combined, as comprehensively as possible, to address these goals in an integrated and transdisciplinary manner.

An integrated approach provides a way to look at the SDGs more holistically but also to explore how these goals might interact with other frameworks such as the Grand Challenges of Engineering (GCE). The GCE consists of 14 projects and engineering-based goals that the engineering community proposes to accomplish by the end of this century (Grand Challenges for Engineering Committee 2008). They include: advance personalized learning; make solar energy economical; enhance virtual reality; reverse-engineering the brain; engineer better medicines; advance health informatics; restore and improve urban infrastructure; secure cyberspace; provide access to clean water; provide energy from fusion; prevent nuclear terror; manage the nitrogen cycle; develop carbon sequestration methods; and engineer the tools of scientific discovery.
The SDGs and the GCE goals have much in common. The integrated nature of these two sets of goals inherently implies that translating progress of one could directly be tied to the progress of another. For example, accomplishing economical solar energy and providing energy from relatively environmentally-friendly nuclear fusion from the GCE could satisfy SDG 07 (Energy), but it will significantly forward the success of many others. The GCE for restoring and improving urban infrastructure is closely tied with SDG 09 (Infrastructure) and SDG 11 (Cities). Likewise, the Paris Climate Agreement shares significant linkages with all the SDGs (Northrop et al. 2016), since environmental sustainability is a core tenant of the SDGs and a pillar of sustainable development. Finally, SDG 03 (Health) would benefit from reverse-engineering the brain, better medicines, and advancing health informatics. Some connections are less obvious but still equally important, for example, data monitoring for the SDGs could benefit from a more secure cyberspace.

An additional value proposition in addressing the linkages between the SDGs and the GCE goals is potential collaboration between different organizations sharing similar interests. This would aid them in avoiding redundancies and in identifying other groups that have already found solutions to problems they might be facing. Doing so would speed up implementation of projects and reduce overall research-related expenses. Discovering the linkages among these various frameworks and systems could aid in discovering unique pathways to complex problems that would go otherwise unnoticed. Reverse-engineering of the brain, for instance, could greatly reduce the cost of computational power by greatly enhancing processing speeds of computer systems. This in turn enables developing countries access to cheaper and more efficient information and communication technology (ICT). Likewise, giving better access to the internet could provide people in developing countries a vastly improved access to everything from finance institution, market prices of their goods, online education, and so on. In addition, access to ICT systems in developing countries could also increase the transparency of their government reducing corruption and improving the capacity to implement other social improvements assuming effort placed in improving SDG 16 (Governance) and SDG 17 (Partnerships). In summary, an integrated approach to the SDGs would bring about a greater understanding of the complexities of sustainable development and illuminate clearer paths to possible solutions to world development problems.

Advocating for a greater involvement of engineers in addressing the SDGs

Engineers and scientists have not been asked to play a significant role in formulating the SDGs and in developing the goals’ indicators and measures. It should be noted that the authors of the SDGs were mostly heads of state and government and high representatives, which means that the process of creating the actual goals and their targets was largely politicized (United Nations General Assembly 2015). Political consensus or partisan compromise drove the process rather than academic consensus and the rational deliberation among relevant multidisciplinary experts. The difference between political consensus and academic consensus is small but significant. First, a consensus is a general agreement, a shared opinion, or a long-standing dogma or paradigm to which most members of a group subscribe. Second, consensus might be reached by different sources (political vs. academic) about the same topic and at different times. For
instance, a political or public consensus may lag any academic consensus, as exemplified by climate change and other complex and ill-defined issues. Example: the research of 97% of publishing climate scientists corroborate that climate change is occurring and is primarily human-caused (Cook et al. 2013), but only 65% of American’s believe the same, which is still a record high (Gallop 2016). Had the public and political consensus matched academic consensus, these two figures should be roughly the same.

Political consensus seems to have more in common with an opinion than an academic consensus. In theory, the focus of politics seems to be about making as many people as happy as possible, so more frequently than not the most popular opinion is the consensus. Ideally (in a Positivists manner), the focus of academic consensus is to strive for objectivity using the scientific method, which is designed to remove bias and strives to identify the most likely truth based on empirical findings. But because the academic consensus involves people, it could also be subject to human error and bias, which could be mitigated, at least in part, by following a scientific methodology and long-standing academic rigor.

The SDGs were devised largely from political consensus, not scientific consensus, which is where the problem of addressing and implementing these goals in depth resides. The best way to accomplish the mission of sustainable development is to research, plan, and act, not guess and act. There is no doubt that the people in charge of drafting the SDGs had good intentions, but they stopped short of promoting and integrating science, engineering, and technology in addressing the goals. Simply put, the contribution of science, engineering and technology is needed to better define the goals, their targets, and their respective success indicators. This can be done by creating a “community of practice” in which development practitioners and researchers are involved as the SDGs are being addressed between now and 2030. Engineers have a critical role to play in that community of practice and need to acquire a broad body of knowledge and adopt a system thinking mindset.

The integrated nature of the SDGs requires many disciplines (e.g., engineers, policymakers, economists, development practitioners, etc.) working together outside of their individual academic silos. The critical role of engineering in addressing the pressing, large-scale societal challenges spanning civilizations across the planet is widely recognized. Since engineering functions as the crossroad between science and technology and society and nature, it is critical for fostering sustainable development and, therefore, implementing the SDGs. In fact, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) has identified dozens of sub-disciplines within engineering that have an crucial part to play in international sustainable development (UNESCO 2010). The literature contains many references to how engineers could become directly involved with the SDGs and sustainable development in general (Roberts 2002; Kelly 2010; UNESCO 2010; World Federation of Engineering Organizations 2015).

**System thinking habits in engineering education**

Engineers interested in addressing the SDGs or parts thereof (targets and indicators) in an integrated manner need to acquire a systems-thinking mindset as early as possible in their education. According to one definition, “systems thinking is the art and science of making
reliable inferences about behavior by developing an increasingly deep understanding of underlying structure (Richmond 1994).” Yet another sees systems-thinking as a new mindset with both depth and breadth and “an iterative learning process in which we replace a reductionist, narrow, short-term, static view of the world with a holistic, broad, long-term, dynamic view, reinventing our policies and institutions accordingly (Sterman 2006).”

Engineers already work with and within systems. Civil engineers are prime examples, since by their very nature they deal with various interconnected infrastructure systems. Civil infrastructure involves the interactions of humans and the economy (social systems) with transportation, energy and electrical, water, sanitation, etc. (physical systems). Information and communication networks improve the functionality of those systems, while political systems of governance are required to make sure those systems are built and maintained. Furthermore, all other kinds of engineers (e.g., electrical, environmental, energy, etc.) must work with not just civil engineers, but social scientists that understand the human and social systems, as well as a myriad of other fields. These interconnected networks form the foundation for society and the basis for sustainable development. Without these systems working correctly and synergistically, the planet could not sustain more people; in fact, many scholars and experts believe that we, as a species, are already over our planet’s available biocapacity, which is a term signifying the available population that can be sustained without degrading the environment. This is exemplified by the fact that in 2016, the human species used all the resources mathematically available to them by August 08, a date getting earlier each year. Systems thinking enables engineers to better implement the SDGs which require interconnected networks of various disciplines working together for a common goal. Engineers require not just analytical skills, creativity, and a wide breadth of education but also a systems thinking mindset (UNESCO 2010).

Even though systems thinking sounds forward thinking and is often used in public discourse and debates in science, engineering, politics and economics, its value proposition to deliver better and more integrated solutions and policy decisions to complex problems is still not accepted by all (Dent 2001). Thus, it is not yet mainstream in secondary and tertiary education where linear cause to effect (deterministic) thinking is the norm. As noted by Dent (2001), terms such “systems approach, systems thinking, and systems view” are not commonly understood. One of the limiting factors for not being mainstream is that systems thinking requires the “thinker” to embrace a new mindset and adopt different habits from those used in reductionist thinking. These habits are best described by the Waters Foundation, based in Pittsburgh, PA and are listed in Table 1. Even though these habits were developed in the context of integrating systems thinking in K-12 education, they apply to a wide range of situations where the thinker is faced with complex issues associated with so-called messy, wicked, or ill-structured problems, such as those involved in sustainable human development. These habits can also be understood as thinking strategies (visual, listening and speaking, and kinesthetic) that a decision-maker might want to follow to address complex problems (Waters Foundation 2016) such as those associated with each SDG and their interconnections.
Table 1. Habits of systems thinkers (Waters Foundation 2016)

- Seek to understand the big picture
- Observe how elements within systems change over time, generating patterns and trends
- Recognize that a system’s structure generates its behavior
- Identify the circular nature of complex cause and effect relationships
- Make meaningful connections within and between systems
- Change perspectives to increase understanding
- Surface and test assumptions
- Consider an issue fully and resist the urge to come to a quick conclusion
- Consider how mental models affect current reality and the future
- Use understanding of system structure to identify possible leverage actions
- Consider short-term, long-term, and unintended consequences of actions
- Pay attention to accumulations and their rates of change
- Check results and change actions if needed: “successive approximation”
- Recognize the impact of time delays when exploring cause and effect relationships

It should be noted that the integration of systems thinking in addressing development issues has been a top priority in the education of undergraduate and graduate engineering students interested in engineering for developing communities and international development at the University of Colorado at Boulder. A new undergraduate/graduate cross-listed course titled *A Systems Approach to Global Engineering* developed by the second author has been offered twice to senior and graduate engineering students. The purpose of this course is to introduce engineering students to the global context in which engineers are asked to operate in the 21st century. The course also aims at introducing students to system dynamics tools and other decision-making tools (e.g., network analysis, multi-criteria decision analysis, etc.) necessary to analyze the uncertainty and complexity inherent in global projects. Part of the course focuses on using system dynamics tools to capture the interactions at play across the 17 SDGs and to show how the engineering profession contributes to the SDGs. At the end of this course, students are expected to:

- Have the ability to identify the multiple dimensions of engineering projects in a developed or developing country context and their relation to meeting the SDGs;
- Be aware of the role non-technical issues may play in their technical decision-making;
- Appreciate the multi-cultural, social, and economic dimensions of practicing engineering;
- Understand the global interconnectedness of SDG related issues at different scales from the local to the global;
- Formulate problems and their solutions in a more systemic and integrated way;
- Be able to approach a wide range of simple, complicated, and complex problems often characterized by different levels of uncertainty; and
- Be familiar with a range of decision-making tools.

These seven goals are met through a combination of lectures, seminars, and term projects. Throughout the course, students are exposed to a variety of development projects and are shown how technical and non-technical issues help in shaping the project outcome.
The course mentioned above fits into a new epistemology of engineering education that is much needed to address the complex problems faced by civilization today. It requires looking at the world’s problems in a more holistic way and being able to interact with a wide range of technical and non-technical stakeholders from various disciplines and walks-of-life, rather than remaining in traditional silos of technical expertise and schools of thought. This new epistemology of engineering education also promotes reflective and adaptive practice, system thinking, engagement, and fieldwork. Finally, it promotes a humanization of the engineering profession and emphasizes that engineering is above all - and has always been - about people.

Analyzing the integrated nature of the SDGs

Integrating the SDGs in engineering education requires developing a curriculum with course material that gives students the opportunity to: (i) discover and become familiar with each SDG; (ii) become aware of their linkages; and (iii) consider their integrated nature when proposing solutions to global development problems.

The integrated nature of the SDGs can be investigated in several ways. One way proposed in this paper is to look at the two-way interactions between the SDGs and present these interactions in the form of a 17-by-17 table as shown in Figure 2. In this two-sector tabular representation, the off-diagonal boxes represent the feedback mechanisms that exist as two SDGs interact in an inter-dependent manner. The double causality table in Figure 2 can be used to assess the level of direct influence (rows) and dependence (columns) of one component onto the others (Arcade et al. 2014). Hence, it can be used to assess the influence and the dependence of one SDG on the others. In general, the strengths of the influence between two SDGs can be described qualitatively using qualifiers such as high, medium, or low, or scored semi-quantitatively over an appropriate range, say, between 0 for no influence up to 3 (or larger as desired) for high influence. The selected scoring range is specific to the SDGs being addressed and the context in, and scale at, which the SDGs are being addressed.

A semi-quantitative approach, presented in Table 2, is an example on how to score the enabling or constraining influence of one SDG on the others. The scoring methodology was adapted from that proposed by Nilsson et al., (2016) to map the interaction between the sustainable development goals. A score ranging between +3 (most positive influence) to -3 (most negative influence) was assigned for each SDG-to-SDG interaction as shown in Table 2. Illustrative examples for each score-level are also proposed in the right column of the table.

Table 2. Scale of sustainable development goals’ interactions (Nilsson et al. 2016)

<table>
<thead>
<tr>
<th>Strength, Title</th>
<th>Explanation</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>+3, Indivisible</td>
<td>Inextricably linked to the achievement of another goal. Accomplishing this goal will accomplish another goal by default.</td>
<td>Ending all forms of discrimination against women and girls is indivisible from ensuring women’s full and effective participation.</td>
</tr>
<tr>
<td>Strength, Title</td>
<td>Explanation</td>
<td>Examples</td>
</tr>
<tr>
<td>----------------</td>
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</tr>
<tr>
<td>+2, Reinforcing</td>
<td>Aids the achievement of another goal. This goal will by default achieve a significant portion of another goal, with only a relatively small amount of work required to further accomplish both.</td>
<td>Providing access to electricity reinforces water-pumping and irrigation systems. Strengthening the capacity to adapt to climate-related hazards reduces losses caused by disasters.</td>
</tr>
<tr>
<td>+1, Enabling</td>
<td>Creates conditions that further another goal’s progress. This goal could be a tool to accomplish another. There is positive overlap.</td>
<td>Providing electricity access in rural homes enables education, because it makes it possible to do homework at night with electric lighting.</td>
</tr>
<tr>
<td>0, Neutral</td>
<td>No significant positive or negative interaction. The interconnections between two goals are purely indirect, if they exist at all. The positive and negative impacts are equal.</td>
<td>Ensuring education for all does not interact significantly with infrastructure development or conservation of ocean ecosystems.</td>
</tr>
<tr>
<td>-1, Constraining</td>
<td>Limits options on another goal. This makes another goal noticeably more difficult to accomplish.</td>
<td>Water requirements for thermoelectric power generation reduce available water for WASH. A climate change can constrain the options for energy access.</td>
</tr>
<tr>
<td>-2, Counteracting</td>
<td>Clashes with another goal. Unless direct actions and efforts are taken by people then this goal will make it significantly more difficult for another to be achieved.</td>
<td>When a population consumes more, economic growth can counteract waste reduction and climate mitigation and degrade the environment.</td>
</tr>
<tr>
<td>-3, Canceling</td>
<td>Makes it impossible to reach another goal. Nothing can be done to have these two goal coexist.</td>
<td>Fully ensuring public transparency and democratic accountability cannot be combined with national-security goals.</td>
</tr>
</tbody>
</table>

The influence and dependence approach belongs to a larger family of methods associated with Cross-Impact Analysis, which originated in the mid- to late-1960s (Glenn 1994). The cross-impact analysis was initially developed to analyze “weak [soft] structured systems” for which mathematical models could not be developed. Since its inception, cross-impact analysis has been seen as a general method for assessing the “interrelations between the most important influential factors in a system by experts who evaluate [subjectively] pairs of these factors” (Weimer-Jehle 2006). The different methods of cross-impact analyses differ on how the interrelations are formulated (probabilistically or deterministically) and whether a qualitative or quantitative approach is used. Cross-impact analysis is a soft systems approach which focuses more on the systemic process to understand a problem situation than its detailed structural components (Checkland and Poulter 2006).
<table>
<thead>
<tr>
<th>Dependence (D) Columns</th>
<th>Influence (I) Rows</th>
<th>Total (+)</th>
<th>Total (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG 01</td>
<td>0</td>
<td>-8</td>
<td>9</td>
</tr>
<tr>
<td>SDG 02</td>
<td>3</td>
<td>12</td>
<td>-5</td>
</tr>
<tr>
<td>SDG 03</td>
<td>3</td>
<td>14</td>
<td>-2</td>
</tr>
<tr>
<td>SDG 04</td>
<td>2</td>
<td>29</td>
<td>0</td>
</tr>
<tr>
<td>SDG 05</td>
<td>3</td>
<td>21</td>
<td>3</td>
</tr>
<tr>
<td>SDG 06</td>
<td>3</td>
<td>31</td>
<td>0</td>
</tr>
<tr>
<td>SDG 07</td>
<td>3</td>
<td>19</td>
<td>-6</td>
</tr>
<tr>
<td>SDG 08</td>
<td>3</td>
<td>19</td>
<td>6</td>
</tr>
<tr>
<td>SDG 09</td>
<td>2</td>
<td>17</td>
<td>-5</td>
</tr>
<tr>
<td>SDG 10</td>
<td>3</td>
<td>2</td>
<td>-2</td>
</tr>
<tr>
<td>SDG 11</td>
<td>1</td>
<td>21</td>
<td>-1</td>
</tr>
<tr>
<td>SDG 12</td>
<td>2</td>
<td>18</td>
<td>-3</td>
</tr>
<tr>
<td>SDG 13</td>
<td>1</td>
<td>-1</td>
<td>9</td>
</tr>
<tr>
<td>SDG 14</td>
<td>-1</td>
<td>6</td>
<td>-3</td>
</tr>
<tr>
<td>SDG 15</td>
<td>2</td>
<td>11</td>
<td>-4</td>
</tr>
<tr>
<td>SDG 16</td>
<td>3</td>
<td>44</td>
<td>0</td>
</tr>
<tr>
<td>SDG 17</td>
<td>3</td>
<td>39</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>36</td>
<td>294</td>
<td>372</td>
</tr>
<tr>
<td>Total (+)</td>
<td>37</td>
<td>-78</td>
<td>372</td>
</tr>
<tr>
<td>Total (-)</td>
<td>-1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 2. Impact matrix of the SDGs. The ratings ranging between +3 and – 3 are listed in Table 2.
Figure 3. SDGs influence (I) vs. dependence (D) diagram

Figure 4. Values of influence, dependence, influence ratio, net influence, and priority index
Figure 2 shows that the double causality table has a total of $Q = n^2 - n = 272$ interactions where $n = 17$ (number of SDGs). The diagonal terms are assumed to be 0 since they represent a goal influencing itself, which mathematically double-counts the strength of interactions. Using a report that analyzed the linkages among the SDGs (Baptiste and Martín-López 2015), our understanding of international development, and the SDGs themselves, the first author generated the scores shown in Figure 2. It should be noted that the analysis presented below is conditional on the chosen scores and context dependent.

The total influence and dependence of each SDG onto the others were calculated. The total influence level of each SDG and its total positive and negative influence on the others are shown on the right-hand side of the impact matrix in Figure 2. Likewise, the total dependence of each SDG and its total positive and negative dependence on the others are shown at the bottom of the impact matrix in Figure 2. The total influence and dependence scores for each SDG are plotted in Figure 3 following the methodology proposed by (Arcade et al. 2014). A graph such as Figure 3 can help differentiate between the variables (i.e., goals) that are either: (i) relay variables (goals), which because of their high influence and dependence, could be sources of instability; (ii) influential variables (goals) showing little dependence but high influence that according to Arcade et al. act as “factors[s] of inertia”; (iii) excluded variables (goals) with low influence and dependence; (iv) dependent variables (goals) with high dependence and low influence; and (v) regulating variables (goals) that lie near the center of the graph. It is important to note that these categories of goals do not have discrete boundaries but fall on a sort of multi-dimensional spectrum, and a given goal may have several characteristics.

Influential goals represent the goals that are the foundation of the dependent goals, which we also define as resultant goals. These resultant goals generally represent the desired outcome of the interconnections. For the SDGs, this is indeed true. Poverty eradication (SDG 01) and inequality reduction (SDG 10) are the main reasons for the creation of the SDGs in the first place, and of all 17 goals these two are the most dependent on the others. To accomplish any positive impact on the resultant goals (poverty and inequalities), focusing on the influential goals is required (Arcade et al. 2014).

Analysis of Figure 3 indicates that: SDG 01 (Poverty) and SDG 10 (Inequalities) are clearly dependent goals because they are found near the bottom-right part of the graph; SDG 13 (Climate Change), SDG 14 (Oceans), and SDG 15 (Land) are excluded goals, being on the bottom-left; and SDG 16 (Governance) and SDG 17 (Partnerships) are highly influential goals, as they are on the top-left. Likewise, SDG 05 (Gender Equality), SDG 08 (Economy), and SDG 09 (Infrastructure) are near the diagonal line near the graph’s center, which per Arcade et al. (2014) represent high stake variables and regulating goals. Finally, the remaining goals do not strongly fall in one category or another; for example, SDG 02 (Food Security) and SDG 03 (Health) fall roughly between the regulating and dependent goal areas in Figure 3.

Goals that are clustered near the diagonal line on the graph have similar influence and dependence values meaning that these goals are not significantly influential or dependent, overall. A focus on these goals is much more tactical than focusing on the influential goals. They
might not improve all the other goals, but they could improve a specific goal. If a policymaker wants to spur energy and economic development, specifically, then allocating resources to infrastructure (Goal 09) makes sense Arcade et al. (2014).

From the total influence and dependence scores of Figure 2, three additional indices were calculated for each SDG and are listed in Figure 4. The first index, the net influence (NI) was calculated as the difference between influence and dependence. The NI shows the absolute power of the goal. The larger the NI the more “powerful” that goal is in causing change to the other goals. The second index is the influence (I)-to-dependence (D) ratio (IR = I/D). It focuses more on the efficiency of a goal to elicit change on the other goals.

SDG 01 (Poverty) and SDG 13 (Climate Change) presented a unique challenge in determining IR since their influence values were negative, implying that they were dependent overall and not influential. Negative values slightly skewed the data because the IR ratio had to be positive to function properly. Zero values presented an additional challenge due to the division by zero. To handle both challenges, the following algorithm was used to calculate IR for each goal, where: ‘D’ is dependence, ‘I’ is influence, ‘IR’ is the influence ratio, and the subscript ‘x’ denotes a specific SDG (x=1-17):

<table>
<thead>
<tr>
<th>If D...and...</th>
<th>( I &gt; 0 )</th>
<th>( I = 0 )</th>
<th>( I &lt; 0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D &gt; 0 )</td>
<td>( IR = \frac{I_x}{D_x} )</td>
<td>( IR = 0 )</td>
<td></td>
</tr>
<tr>
<td>( D = 0 )</td>
<td>( IR = 48 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( D &lt; 0 )</td>
<td>( IR = \frac{I_x}{I_x +</td>
<td>D_x</td>
<td>} )</td>
</tr>
</tbody>
</table>

Finally, the third index is the priority index (PI), which is a proportionally weighted-average of the influence ratio (IR) and net influence (NI) relative to the largest value for each set of goals. It is defined as follows:

\[
PI = A \frac{IR_x - \min IR}{\max IR - \min IR} + B \frac{NI_x - \min NI}{\max NI - \min NI}
\]

\( A \): weight of influence ratio
\( B \): weight of net influence
\( \min \): minimum value in set of all goals
\( \max \): maximum value in set of all goals

This index ranges between 0 and 1 with small values indicating goals with low priority and high values representing high priority goals. Our analysis assumed equal weights (\( A = B = 0.5 \)) for both IR and NI. There could be specific circumstances, however, where the weights are not the same; their sum must always be equal to 1. If policymakers want to focus on generating as much impact as possible regardless of efficiency of distributing resources, then they would focus solely on the NI and select \( B = 1 \) (\( A = 0 \)). Conversely, \( A = 1 \) (\( B = 0 \)) would correspond to the most efficient allocation of resources as opposed to absolute impact.
Dependence is likened to input, and influence is related to output. The influence ratio shows the efficacy of a goal. A large ratio shows that a small allocation of resources for that goal will yield relatively large benefit in terms of indirect impacts. The higher the IR, the more it helps accomplishing the other goals. The net influence tells the likely size of that absolute impact. Although similar, they tell two different pieces of information. Just because the ratio is large doesn’t necessarily indicate it will have a large impact. Consumption (Goal 12) is an example: it has the largest ratio but is fourth for NI. Goal 12 will produce the highest amount of good, or utility, relative to its cost, but it will not generate the most-good in absolute terms. It will be cheaper to allocate resources with the highest relative pay-out, but if the desire is the greatest overall impact, then Goal 16 or 17 would be better.

Using the IR and NI together should aid policymakers in identifying what is best for their situation, which is why the priority index was introduced. Poorer countries might elect to focus on the influence ratio, since resources are scarce, but richer countries might want to focus on a higher net influence to see positive change faster. In short, the main differences are relative vs. absolute and efficiency vs. cost for influence ratio and net influence, respectively. Either way, an influence ratio below one and a net influence below zero should be avoided. Only when significant progress is made on the more attractive goals should the dependent goals be seriously allocated resources.

**Prioritizing the SDGs**

Both the influence ratio and priority index were used to produce a priority ranking of the SDGs based on where the SDGs are positioned in the influence versus dependence diagram and the tables in Figure 3 and 4. The pillars of sustainable development (economic, social, political, and environmental) are shown as four (of five) shaded boxes in Figure 5. Each SDG falls into one of those four pillars. Although by their very nature SDGs cross-cut multiple pillars, they are primarily assigned to just one of those pillars where their influence was greatest. The political pillar was placed in the same column as the social pillar as they are highly interrelated, even more so than the other pillars; this assumption that was made in defining the original three economic, social, and environmental legs of sustainability (Thwink.org 2014).

Besides the four pillars, poverty (Goal 01) and [economic] inequalities (Goal 10) represent the desired overarching goals to which the other goals strive to contribute and improve. They fall in the fifth shaded box (desired socio-economic results) of Figure 5. Poverty eradication is the ultimate social outcome, while reducing inequalities is the desired economic outcome of the SDGs and is closely associated with poverty. Figure 5 shows the SDGs by levels of priority with higher priority index values (more influential than dependent) at the bottom and those with lower priority index values (more dependent than influential) at the top.
Two types of arrows are used in Figure 5, directional and concurrent. Directional arrows have an order and are such that significant progress is needed in a prerequisite goal before resources can be seriously allocated for a subsequent goal. For instance, SDG 04 (Education) must occur prior to SDG 05 (Gender Equality). Concurrent arrows on the other hand are requisites. SDGs, or groups of related goals, connected by concurrent arrows should be prioritized together because they are closely interconnected; there could be detrimental effects if both SDGs aren’t prioritized together. Specific examples include SDG 12 (Consumption) with SDG 16 (Governance) and SDG 01 (Poverty) with SDG 10 (Inequalities).

Furthermore, all the economic development SDGs must be undertaken with high consideration for the environment sustainability-related SDGs. Concurrent arrows also imply that the connecting SDGs must be considered equally when either one is prioritized. Concurrency is crucial for environmental sustainability, as the environment is important for all the goals. Inequality and poverty are highly interconnected and both represent the desired outcome of the SDGs. The issues of food security, health improvement, strong governance, and so on are important, but they are requirements for and feed into poverty eradication and inequality. For this reason, SDG 01 and SDG 10 are placed at the top. Only when all the other goals have made significant progress, should poverty and inequality be directly addressed. Food security is the last social development goal; the economy is the last economic development goal; and climate change is the last environmental sustainability goal. These feed directly into poverty and inequality.

Figure 5. Prioritization flowchart indicating the order that accomplishes the SDGs most efficiently. The priority index value for each SDG is given in parentheses.
Concluding remarks and future work

The paper focuses on a high-level analysis of the SDGs including determining their linkages and priority levels, as opposed to a low-level analysis of the targets underlying the SDGs. The results of the analysis show that the SDGs need to be considered in an integrated manner. They also show that, in their current formulation, the SDGs have different levels of influence and dependence on each other. This, in turn, implies that the SDGs carry different priorities. These conclusions need to be taken under consideration when exploring the contribution of engineers in addressing the SDGs, whether in engineering course curriculum development or in policy decision making.

The analysis presented in this paper depends on the values included in the SDG impact matrix of Figure 2. In this paper, the values selected by the authors were thought to be representative of the interactions of the SDGs for an average country in an average situation. As such, the proposed analysis can be understood as a proof-of-concept, i.e., a methodology that can be used by policymakers. Country-specific data and understanding is needed to populate the SDG impact matrix for addressing the linkages between the SDGs in each country context and at a given spatial scale.

Analysis of the linkages and priority levels of the SDGs at the goal level is a good start, but it only produces a general idea of how the goals are connected. To attain a better understanding of their linkages, a more advanced methodology needs to be carried out at the target level. The influence and dependence of each goal on the others can also be inferred by using the connections that exist between targets. Targets (and some of their indicators) cut across many goals and act as an underlying connectivity among the goals but not the other way around (Weitz et al. 2014). The challenge in addressing linkages at the target level resides in the sheer quantity of interconnections that need to be analyzed: 28,392 among targets compared to 272 among goals. Analysis of this large number of linkages requires research personnel and an academic approach. This is where higher education and research institutions could play a critical role in the future.

The engineering profession has a crucial role to play in analyzing, understanding, and implementing the SDGs and their targets by 2030. Engineers could bridge the gap between the policymakers that created the SDGs and the people who are forced to live with the outcomes of their decisions. Without accounting for the integrated nature of the SDGs in decision-making and only considering the SDGs in isolation, there is potential to: (i) harm those whose lives need to be improved; (ii) waste large amounts of resources; and (iii) disenfranchise people away from aid and development. These undesirable outcomes would cause feedback mechanisms that could make sustainable development even more difficult to implement in the years to come.
References


