Goal Modeling for Sustainability: The Case of Time

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***Abstract*—Goal models have established themselves as a means to capture often conflicting needs of stakeholders and reason about how alternative solutions may impact those needs, allowing for trade-off assessments at the early stages of development. More recently, goal models have been extended with the notion of indicators that allow quantitative, real-life measurements to be used in addition to qualitative measurements to more precisely assess trade-offs. While goal models are most often used in the context of systems or software development, they are well suited to any type of development effort that involves a large set of diverse stakeholders. Sustainability Engineering is an emerging discipline that fits this profile, requiring everyone from individuals to large communities to be considered to maximize social benefit while minimizing negative ecological impact. This paper proposes a method to combine the high-level, qualitative assessment from goal models with the rigorous, detailed, quantitative sustainability assessment based on time cost that is applicable to varied types of development projects. The method is demonstrated through a development project from the construction industry and modeled with the Goal-oriented Requirement Language.**

***Index Terms*—goal modeling, stakeholder trade-offs, decision making, sustainability, sustainability engineering, indicator, qualitative measurements, quantitative measurements, time, GRL, Goal-oriented Requirement Language.**

I. It's About Time

Traditional engineering is a process of maximizing utility while minimizing cost to the client. Sustainability Engineering must vastly expand these concepts to become a process of *maximizing social benefit while minimizing negative ecological impact*. A sustainable solution to a problem must address *societal needs* at multiple scales (those activities that prevent degradation of some aspect of the individual, the family, or the community as a whole). Ultimately, a sustainable solution improves the *quality of life* of the community [1]. To this effect, a method is needed that allows the most sustainable alternative to be identified while considering a large number of stakeholders, from individuals to whole communities. Such a method must focus on the *efficiency* by which people use their time to meet their needs, but also on the *effectiveness* of how people use their time to meet their needs.

Quality of life can be achieved through a combination of *technological development* (i.e., large-scale software systems, air or land transportation infrastructure…) and *human development* (education, health, eliminating poverty…). The first aims to improve the efficiency of a community in using time to meet its needs, while the latter takes effectiveness at the individual and other levels into account. This paper proposes *Goal-Oriented Engineering for Sustainability (GOES)*, a combination of a Sustainability Engineering approach that assesses alternatives for a technological development and a Goal Modeling [6][11][28][31] approach to reason about how human development will act in concert with technological development as illustrated in Fig. 1.

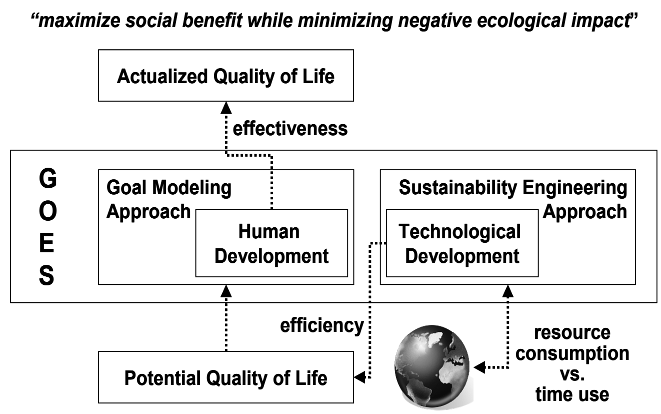

Fig. 1. Goal-Oriented Engineering for Sustainability (GOES).

Sustainability Engineering methods such as the Triple Bottom Line [8], which are commonly used today, may result in solutions that are sustainable within some communities, and not in others, when the expanded Daly Rules are taken into account. The original Daly Rules [7] work on a planetary level and ensure that resources are not used faster than they can be replenished and that waste is not emitted faster than can be absorbed. The expanded Daly Rules, however, take communities into account and ensure that the resources and time used for a development are available within the community undertaking a development. To address these weaknesses, GOES proposes to use a Sustainability Engineering approach that is being developed by one of the co-authors and currently discussed in the Sustainability Engineering community [17].

To assess efficiency, the proposed Sustainability Engineering approach introduces a relationship between the time it takes for community members to meet their needs and the resources consumed by the community. The proposed method uses this relationship to convert excessive resource consumption into a *time cost* to the community based on a life

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cycle analysis for each alternative, using human time as the unit of measure [17]. Any alternative that produces a positive net time benefit to the community is sustainable. The alternative that produces the maximum net time benefit is the most sustainable.

While the proposed Sustainability Engineering approach can determine whether there is a net time benefit or not for a planned development, the approach by itself cannot make a community more effective at using their new-found time. The proposed approach results only in an assessment of *potential quality of life*. People could use their gained time for paid employment, getting a higher education, or self-destructive behaviours. The proposed Goal Modeling approach allows individuals, communities, and policy makers to reason about the usage of the new-found time and its impact on the ultimate goal of *actualized quality of life*, thus addressing the effectiveness of the proposed development.

The contribution of this paper is the combination of Sustainability Engineering and goal-oriented reasoning [4] based on *time cost* to determine the efficiency *and* effectiveness of proposed sustainable solutions. A novel reasoning mechanism is *not* a contribution of this paper, as existing reasoning mechanisms are used for goal-oriented reasoning in GOES. The contribution focuses on a description of the content and structure of the goal model, and required novel Goal Modeling features, in the context of Sustainability Engineering. The paper hence describes a model-driven approach for Sustainability Engineering that can be analyzed with existing techniques for goal models.

In the remainder of this paper, Section II gives an overview of foundational principles of Sustainability Engineering, while Section III discusses the relationship of societal needs and sustainability. This section also introduces the proposed Sustainability Engineering approach, which is based on human time as the unit of measure of sustainable technological development. Section IV then provides background on Goal Modeling with the Goal-oriented Requirement Language (GRL) [3][4][11] as it is applicable to Sustainability Engineering. In Section V, the proposed GOES method is described with the help of an example from the construction industry, i.e., deciding on whether to repair or decommission a bridge over a highway. This section gives a summary on how to determine time cost for the development, demonstrates how goal-oriented modeling can be applied to reason about human development in the context of Sustainability Engineering, and highlights the need for new Goal Modeling features required for GOES. Section VI summarizes related work in the area of requirements engineering for sustainability, while Section VII concludes the paper and discusses future work.

II. Foundational Principles

This section defines key foundational principles of Sustainability Engineering: ecological footprint, human and technological development, and sustainable development.

A. Ecological Footprint

The concept of *ecological footprint* [29] measures the area of land and water required to provide the resources used, and assimilate the wastes produced by a community. It measures this land in *global hectares (GHa)*, which is land being used by the community as if it were as biologically active as land that was as productive as the average global rate. When a community has a larger ecological footprint than the biologically productive land mass they manage, they must 'import' the excess resource consumption from either the future or another community. The ecological footprint is a measure of the minimum amount of land required to support a population indefinitely, based on what we know today, and is an evolving concept. Currently, the world is beyond capacity when measured using this technique [29].

B. Human and Technological Development

Development spans the concepts of human development and technological development. *Human development* [27] can be described as enhancing the freedoms, choices, and opportunities of the people in a community. It is not measured directly, but rather by measuring the impacts on people's lives as a result of the development activities undertaken. Human development is an evolving concept, but is generally understood to include education, health care, eliminating poverty and hunger, promoting gender equality, and other important social issues. Human development focuses on how people use their time to meet their wants and needs more *effectively*. On the other hand from the perspective of the engineering profession, *technological development* for a community focuses – regardless of culture, climate, or technology – on how to use people's time to convert resources into the means to meet their wants and needs more *efficiently*.

In any case, technological development helps people to meet their needs by using resources to reduce the time it takes to perform the specific tasks associated with needs. It typically does this through the creation or enhancement of existing infrastructure (software systems, bridges, roads…), so that time and resources are invested with an expectation of a future return of that investment as time and/or resources.

Technological development facilitates human development by increasing the efficiency of resource utilization by the community with respect to time. It does not infer how effectively people use their time and resources to meet their needs. It can be observed that in a community with ample technology, many people still suffer from family violence, substance abuse, high rates of crime, and other challenges that are indicators that all of the needs of the individual, family, or community are not being met. In many cases, human development is required within such a community.

C. Sustainable Development

The concept of *sustainable development* was first introduced as "development that meets the needs of today without compromising the ability of future generations to meet their needs" [30]. This introduces two concepts which will be discussed further – the idea of *needs*, and the idea that some activities may negatively impact future generations.

While credited to Herman Daly [7], variations on lists of sustainability requirements have been produced by many researchers, and published in a wide range of documents.

Daly's rules are: (1) renewable resources such as fish, soil, and groundwater must be used no faster than the rate at which they regenerate; (2) nonrenewable resources such as minerals and fossil fuels must be used no faster than renewable substitutes for them can be put into place; and (3) pollution and wastes must be emitted no faster than natural systems can absorb them, recycle them, or render them harmless.

Daly suggests that these are minimum requirements to ensure that human activities do not compromise the ability of future generations to meet their needs, but this list is not expected to be sufficient by itself to be sustainable.

Determining sustainable technological development requires an *objective test* that decides which alternative offers the most sustainable solution to a problem, and how sustainable that alternative is. An objective test requires objective measurements, and hence agreed-upon units of measure which the proposed Sustainability Engineering approach argues should be related to time. To find these units of measure, we must expand on the concepts of needs, sustainable development, and potential quality of life, as described next.

III. Needs and Sustainability

A. Needs and Wants

Needs of the individual, the family, or the whole community can be expressed at different levels of abstraction – from vague high level goals that are hard to quantify to specific, more measurable activities of various stakeholders. These activities prevent degradation of some aspect of the individual, the family, or the community as a whole. They are dependent on our human biology and psychology, and are independent of culture. Thus sleeping, eating, drinking, fitness, providing for homeostasis, etc. would meet individual needs, while child care, care for the infirm and elderly, etc. would meet family needs, and education, security, governance, etc. would meet community needs. All of the associated activities required to support these needs would also be needs, so the acquisition, transportation, utilization, and disposal of the resources to meet these needs would be needs by this definition. The tools and infrastructure associated with these needs would be the means to meet the needs, rather than needs themselves. For example, while food is a need, employment used to purchase food is a means to meet the need.

While the definition of needs can be common between individuals or communities, the importance of needs may differ between individuals or communities, respectively. Each individual or community must decide for themselves how important each need is, what the *boundaries* of those needs are.

There are some activities that are not categorized as needs but rather as *wants*, because they do not prevent the degradation of some primary aspect of one's life. For example, the desire to own a more expensive car does little in terms of ensuring greater mobility that a cheaper model would not provide. The focus here is on needs.

B. Sustainable Development Revisited

While Daly's rules described earlier are appropriate on a planetary basis, for any scale smaller than that, two additional rules have to be added: (4) the ecological footprint used to meet a community's needs must be managed by the community; and (5) the human time used to meet a community's needs must be available from within the community.

Sustainability is the capacity of a community to ensure its population can meet their needs today and for an indeterminate period of time, using the existing resource base and technology available to the community. It is not expected that the community would be static, and improvements to the quality of life within the community can come from various forms of development. Any community that is over-capacity, however, will not be able to increase consumption of those resources that are over-exploited to produce a positive change in their quality of life.

For this paper, a community is sustainable iff the Daly rules for the community are met, including the amendments above. This is demonstrated by showing that the combination of the change in the potential quality of life and the change in resource consumption is better than the status quo. Sustainable development is hence the process by which *the quality of life of the community is enhanced in such a way that the needs of the community today are met without compromising the ability of future generations to meet their needs*.

A common method in use today to assess the relative sustainability of different alternatives is the Triple Bottom Line [8], which measures the costs and benefits of technological development from economic, social, and environmental perspectives. While this approach clearly will produce results that are 'better' than only looking at the finances of a system, there is no indication that the result of the analysis will be sustainable (e.g., considering the expanded list of Daly Rules). The solutions may be sustainable within some communities, and not in others. To resolve these weaknesses, an alternative approach is required that goes beyond traditional engineering methods. In essence, Sustainability Engineering must be based on a process of maximizing social benefit while minimizing negative ecological impact.

To assess the sustainability of any given alternative, the engineer must be able to accurately estimate the benefit to the community and the ecological impact caused as a result of the alternative. This must include the costs and benefits associated with every development phase (e.g., see Life Cycle Analysis [24] which is already used by many sustainability practitioners in their work today). It is critical to find the 'correct' parameters to use Life Cycle Analysis on. GOES argues that these parameters should relate to time cost as explained below and, if so, meet the requirements of Sustainability Engineering listed above.

There is a relationship between the amount of resources used within a community (measured as ecological footprint) and the time required to meet needs within that community as shown in Fig. 2. As resource consumption goes up, the time required to meet needs goes down, approaching asymptotically to some absolute minimum. This relationship is supported by Canadian Ecological Footprint Data [13] and Canadian Time Use Data [25], and it is expected to be wholly true regardless of community scale, culture, or resource availability. Note that given the granularity of the available data, this relationship is an approximation for the community. Resource usage is expressed in global hectares (GHa/ca), while time use is shown in minutes per day per capita (min/d/ca). For the determination of this relationship, those activities from the Canadian Time Use Data relating to rest, food, water, housing, clothing, fitness, hygiene, sanitation, education, child care, health care, and community development, and the time spent for mobility relating to those activities, are considered to be needs, i.e., those activities represent the boundaries of needs.

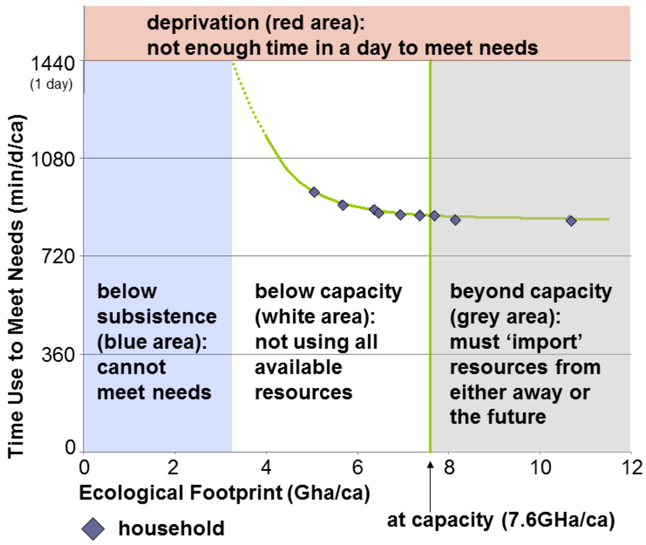

Fig. 2. Relationship between Time Use and Resource Usage (Ecological Footprint) for Canada in 2005.

The capacity of a community is determined by the type of its available land. As shown in Fig. 2, this happens to be the equivalent of 7.6 GHa/ca for Canada. A community operating at capacity is using its resources sustainably. However, any further use of resources would have to be imported from another community or borrowed from the future. In a world that is beyond capacity, those resources that are being imported may not be available in the future. At some time, resources being over-consumed will become unavailable, and the resources available to the community will drop, and therefore the time required to meet needs within the community will go up. In a world that is below capacity, resources can actually be conserved for future use or exported to other communities.

At capacity, the slope of the time/resource curve represents the incremental time cost associated with a loss of resources to that community at some time in the future. The slope at capacity in Fig. 2 is –9.49 min/d/GHa. Any considered alternative is sustainable as long as it results in a change to time use and/or resource usage that is better than this slope at capacity (i.e., the shaded area below the slope in Fig. 3). There are four cases to consider when determining the sustainability of a development based on this slope. The alternative is sustainable, if its slope is steeper and the time/resource relationship places the alternative in the bottom right area (scenario A) or if its slope is flatter and the time/resource relationship places the alternative in the bottom left area (scenario B). On the other hand, the alternative is not sustainable, if its slope is steeper and the time/resource relationship places the alternative in the top left area (scenario C) or if its slope is flatter and the time/resource relationship places the alternative in the top right area (scenario D). GOES represents these scenarios by a unitless *sustainability index* per capita, which is the magnitude of the improvement in time use and ecological footprint, with the sign of that value indicating which side of the line the result is on (positive for the shaded area; the higher the sustainability index, the more sustainable).

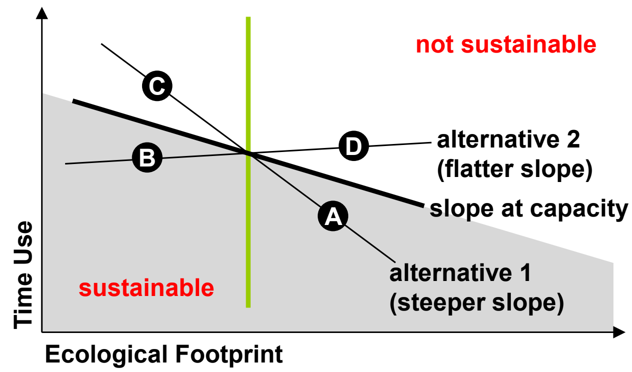

Fig. 3. Sustainability Assessment Based on Slope at Capacity.

In summary, GOES derives from public data the capacity of a community, and a relationship between the time it takes for community members to meet their needs and the resources consumed by the community. The relationship is unique for every community and is sensitive to the boundaries of needs chosen and cultural expectations. By including the concepts relating to ecological footprint, this function can also be sensitive to resource availability. This relationship can be used to convert excess resource consumption into units of time, and thus use human time as the unit of measure of sustainable technological development.

C. Potential Quality of Life

In any 24 hour period, people will spend time eating, sleeping, performing personal care, child care, etc. to meet their needs and the needs of their family and community. If it takes 24 hours per day per person in the community to meet their needs, then they are at a bare level of subsistence.

If the boundaries of chosen needs produces a time/resource curve where the time required to meet needs at capacity exceeds 24 hours per day (i.e., 1440min), they are in a state of deprivation that will lead to famine, disease, and conflict. In this case, no alternatives will exist that would produce an improvement in the potential quality of life within the community through technological development. There would be no investment of resources and time that could produce a return on that investment.

If, due to abundant natural services, efficient division of labour, or some other means, it takes less than 24 hours/day for needs to be met, then the community has time available for other activities. Quality of life within that community has the potential to improve. By maximizing the time available to the population for activities other than those required to meet needs, through the use of technological development, the engineer improves the *potential quality of life* to an optimized state. In addition, human development is required to actualize that potential, so that quality of life itself is maximized.

IV. Goal Models and Sustainability

Goal models [6][11][28][31] are in many ways the ideal candidate to model the assessment of alternatives for sustainable development. First, goal models can express the hierarchy of needs as discussed in Section III.A – from high level goals to specific activities for various stakeholders, because goal models capture the intentions of stakeholders as well as their goals and business objectives. Second, goal models allow to reason about alternatives as discussed in Section III.B and their impact on high-level goals, because goal models (a) allow the explicit definition of alternatives to achieve stakeholder intentions and objectives, (b) capture the weighted contributions of goal model elements on each other, allowing the exploration of positive and negative implications of decisions on stakeholder goals, and (c) can be evaluated [4] to, in this context, assess the effectiveness of human development. Third, recent advances in Goal Modeling have resulted in the inclusion of indicators [11] (i.e., real-life measurements such as those resulting from an assessment of sustainability) in goal models.

While many Goal Modeling approaches such as *i** [31], KAOS [28], and Tropos [6] could be used to model sustainable development, this paper uses the Goal-oriented Requirement Language (GRL) because of its support for indicators, which is missing in i*, KAOS, and Tropos, making it difficult to capture real-life measurements from the sustainability assessment in the goal model and then reason about them in the goal model.

GRL goal models include (i) actors or stakeholders (), (ii) intentions captured with softgoals () or goals () and their AND/OR/XOR-decomposition structure (), (iii) tasks (i.e., solutions to be considered) (), (iv) weighted contributions (→) between solutions and intentions, (v) dependencies between stakeholders (), and (vi) indicators (also called key performance indicators) (). Contributions can be expressed either qualitatively (by labels such as + or –) or quantitatively (by a range from –100 to 100). Satisfaction values for nodes in the goal graph determine the degree with which an element is satisfied. Satisfaction values typically range from –100 (not satisfied at all) to 100 (fully satisfied).

As an example, consider the GRL goal model in Fig. 4, depicting an excerpt of the hierarchy of needs for an individual (representing a group of similar individuals) based on Section III.A. The main goal of the individual is to improve her actualized quality of life. This can be achieved by staying healthy, spending enough time with her family, and earning enough money to put her children through school and to retire. Towards the bottom in the goal hierarchy, tasks represent the needs activities. The tasks contribute either positively or negatively to the higher level goals. For space reasons, the tasks related to food, clothing, shelter, education, personal care, and health care are not shown in the figure. However, this does not change the fundamental structure of the goal model. For three tasks, indicators are also shown. The satisfaction of the resting task is determined by the time spent resting and the quality of the rest. The satisfaction of the task to take care of dependents is satisfied by the time available for this task, as is the task to use transportation.

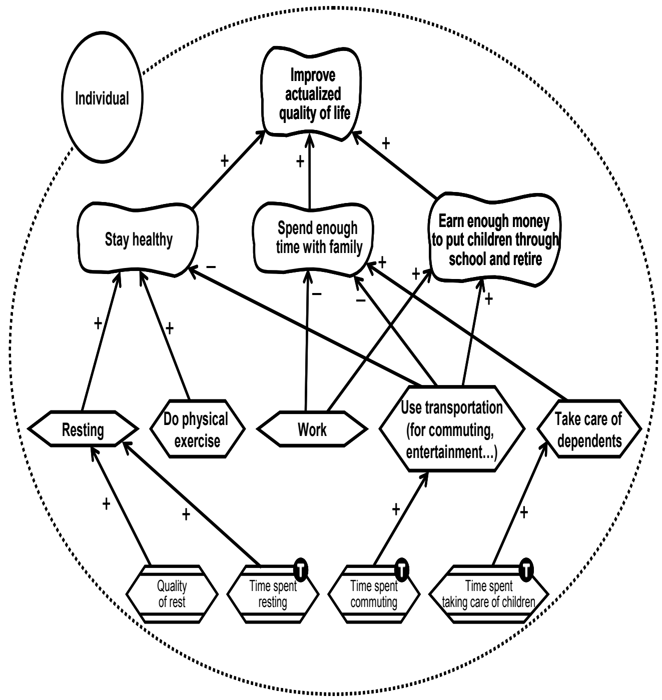

Fig. 4. Goal Model for Needs of an Individual.

Indicators enable the integration of real-life measurements into goal models. An *indicator* converts a real-life value (e.g., 2hrs) to a GRL satisfaction value according to a user-defined *conversion function* compliant with the structure imposed by the URN standard. Several types of conversion functions are available for URN, and URN can be extended with additional functions. For quantitative real-life values, the most common conversion function is based on *best*, *threshold*, and *worst* parameters which are mapped to the GRL satisfaction values of 100, 0, and –100, respectively. Interpolation then determines the satisfaction value corresponding to a real-life value. This is the function used for most indicators in this paper.

The *evaluation* of goals is a core concept in Goal Modeling. This is commonly achieved by providing the goal model with initial real-life values for the indicators as they are typically found at the bottom of the goal graph. These values are first converted into GRL satisfaction values and then used along with weighted contributions and the decomposition structure of the goal model to calculate satisfaction values for all goal model elements (by propagating satisfaction values from the bottom up towards the top of the goal model). In this context, URN allows the definition of a GRL *strategy*, i.e., a set of initial real-life values for indicators or initial satisfaction values of tasks and goals.

URN has been extended with formula-based manipulation of indicators [22], i.e., it is possible to aggregate one or more individual indicators into a higher-level indicator given a mathematical formula defined in the model instead of the default propagation-based method.

While the example in Fig. 4 only shows the goal graph of a representative individual of a particular group, similar goal graphs can be created for a family or whole communities, allowing to reason about the actualized quality of life of a wide range of stakeholders. Note that for other groups of individuals, the contributions in the goal graph may also be slightly different. For example, those who use public transport live a less stressful life and hence the health impact may be more positive. Other groups may use transportation mostly for bringing children to afternoon activities which in fact results in spending more time with the family, but may not contribute to earning more money.

V. Assessment of Development Project

While Sections II and III motivated the use of time cost to assess the sustainability of technological development and Section IV argued that goal models are ideal candidates to assess the needs of individuals as well as whole communities, this section demonstrates how the combined GOES approach is actually applied to one sample development project. The chosen project seeks to determine whether it is more advantageous to repair or decommission a bridge over highway 401 in Oshawa, Ontario, Canada, in terms of sustainability and the impact on the needs of various stakeholders in the community. While this is a fictive development project, it nevertheless resembles reality very closely.

First, the calculations to determine whether the proposed development is sustainable are summarized. Second, the structure of the goal model is described that allows human development to be assessed based on the results of the technological development. This sub-section also points out why current Goal Modeling techniques are insufficient to holistically model sustainability of development projects and describes how goal models may be improved to address these issues through the use of (i) *time indicators* and (ii) *dynamic conversion functions*.

A. Is the Technological Development Sustainable?

As a first step, the scale of the development is determined. In this case, the development affects the local community only. The bridge carries an annually averaged total of 400 local cars per day, and it reduces travel time for the local population by about 9 minutes per car trip. In a second step, the boundaries of needs are determined and in this case all standard needs are included in the assessment as is expected for a city in Canada. The next step establishes the community-specific time/resource curve and the slope of that curve at capacity using Canadian Time Use Data [25] and Ecological Footprint Data for Ontario [9]. The resulting slope is –19.8 min/day/GHa (i.e., the community is made more sustainable through (i) any increased use of the ecological footprint to meet needs as long as it saves the community as a whole more than 19.8 min/day/GHa (see scenario A in Fig. 3) or (ii) any increase in time use of at the most 19.8 min/day/GHa as long as it is sufficiently offset by a reduction in ecological footprint to remain below the slope (see scenario B in Fig. 3)).

Then, the ecological footprint as well as the net time benefit over the life span of the development are calculated compared to the case of doing nothing, considering (i) time and energy costs for equipment, labor, and materials, (ii) the time benefit of saving 9 minutes per car trip, (iii) resource usage for petrochemicals, road salt, and quarried material, as well as (iv) produced waste (further details available upon request).

For the case where the bridge is repaired, this results in a net time benefit of 14 million minutes over 40 years and a reduction of the ecological footprint of 7298 GHa over 40 years, producing a change of the time/resource relationship of 5.27 min/day/GHa. The sustainability index is +0.0076 per capita. Therefore, this case represents scenario B in Fig. 3 (flatter slope, reduction in time use and resource usage), and is hence sustainable. For the alternative case (i.e., decommission the bridge), the calculations yield a net time loss of 24 thousand minutes over 40 years and an increased ecological footprint of 1.75 GHa over 40 years, resulting in 38.7 min/day/GHa, and a sustainability index of –0.0000131 per capita. Therefore, this case represents scenario D (flatter slope, increased time use and resource usage), and is hence not sustainable.

While the sustainability assessment can determine which one of the alternatives to choose from a sustainability point of view, it does not consider whether the new-found time is used effectively by the individuals in the community. This is addressed by the goal models described in the next sub-section.

B. Goal Modeling for Sustainability

The purpose of the goal model is to enable reasoning about human development in concert with technological development. To realize this purpose, the following concepts from Sustainability Engineering have to be captured by the goal model: (1) needs, (2) actualized quality of life, (3) potential quality of life, (4) boundaries of needs, (5) considered alternatives, and (6) any key measurements that are used in the assessment of sustainability as summarized in Section V.A (most notably time measurements). The goal models in this paper are used to convey the structure of the goal model and not to demonstrate an in-depth goal hierarchy. Therefore, exemplary and incomplete goal models are shown.

Needs and Actualized Quality of Life. The needs and actualized quality of life are already covered by the tasks and the top level softgoal, respectively, in a stakeholder's goal graph as seen in Fig. 4.

Potential Quality of Life. The potential quality of life is modeled for a stakeholder in the goal model with the new concept of time indicator (see Fig. 5). A *time indicator* is indicated by T and is a regular GRL indicator with a constraint on its real-life value, in that the value’s unit of measurement must be time-based. However, once the real-life value is converted into a GRL satisfaction value, a time indicator is no different than a regular GRL indicator. Nevertheless, the time indicator is introduced, because time is *the* key concept for GOES, and to indicate evaluation scope as detailed at the end of this section. A flag in the Indicator metaclass of the URN standard identifies a time indicator.

In addition to being time-based, the indicator for the potential quality of life is also formula-based. It is calculated based on the other indicators from Fig. 4, i.e., the real-life values (minutes) of the lower level indicators are summed up to yield the indicator. The *threshold* parameter and *best* parameter of the indicator specify that as soon as the summed minutes of activities are less than a day, the satisfaction value of the indicator is positive. The closer the summed minutes are to the ideal of zero minutes (i.e., the stakeholder does not have to spend any time to satisfy all needs), the higher the satisfaction value of the indicator. Note that the *worst* parameter is somewhat arbitrary as anything beyond a day is already quite bad.

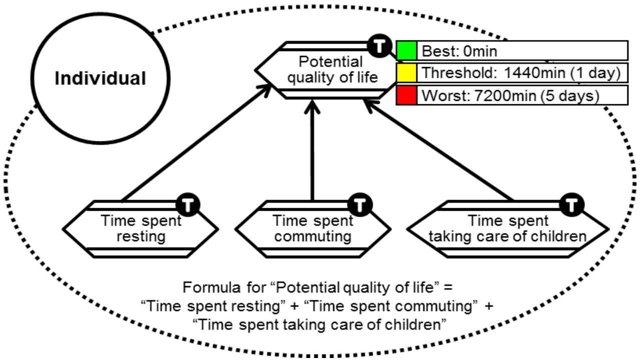

Fig. 5. Indicator Model for Potential Quality of Life.

Boundaries of Needs. The boundaries of needs are simply defined by what is included in the goal models in Fig. 4 and Fig. 5. If a need is not relevant, then its activities are not included in Fig. 4 and its associated indicators are also not included in Fig. 4 and Fig. 5. Hence, at the beginning of the assessment of a development, the content of goal models are systematically created based on the chosen boundaries of needs.

Considered Alternatives. The alternatives are modeled as tasks of the Oshawa municipality that contribute to the overall sustainability goal of the municipality as demonstrated in Fig. 6. The final result of the sustainability assessment (i.e., the sustainability index) is represented in the goal model by indicators – one for each considered alternative. The threshold parameter for these indicators is zero, i.e., a positive sustainability index should result in a positive satisfaction value and a negative sustainability index should result in a negative satisfaction value. The best and worst parameters, on the other hand, have to be determined by the municipality, and reflect the sustainability goals of that community.

Key Measurements. Key measurements such as the sustainability indices as well as the time measurements are already captured in Fig. 4, Fig. 5, and Fig. 6. Note that Fig. 4 also includes non-time related indicators to hint at the possibility of simultaneously reasoning about time-related and non-time related indicators. In Fig. 7, the sustainability index is further broken down into its constituent elements: net time benefit, ecological footprint, and the slope of the time/resource curve. All of these are used to calculate the sustainability index, i.e., the index is again a formula-based indicator (albeit a rather complex one given the calculations described in Section V.A). An instance of the goal model in Fig. 7 exists for each considered alternative (e.g., repair, decommission) and then feeds accordingly into the sustainability indices in Fig. 6.

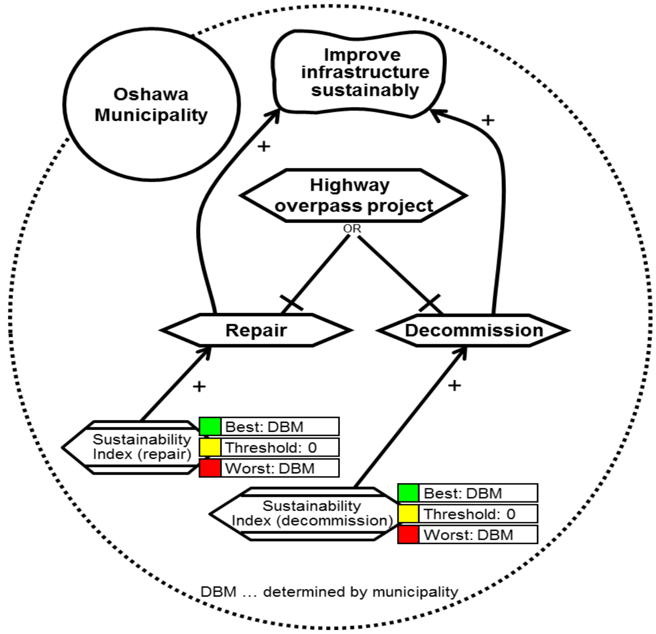

Fig. 6. Goal Model for the Considered Alternatives.

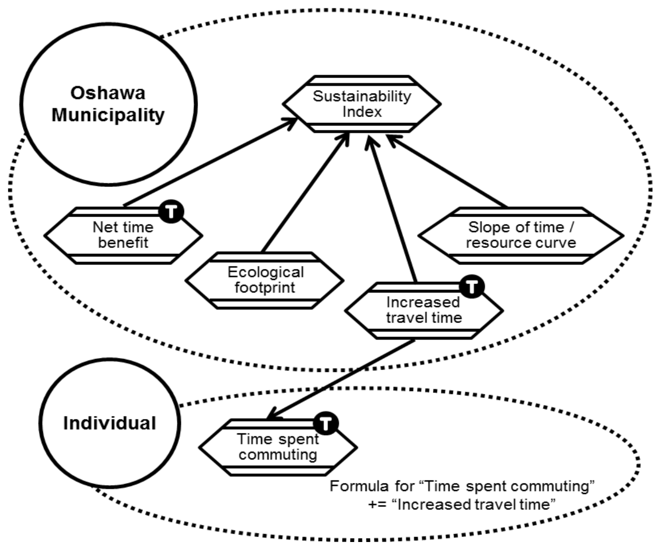

Fig. 7. Sustainability Index and Other Measurements.

In addition to the already mentioned key measurements, any other key measurement that is useful in the assessment of the development is also included in the goal model and linked accordingly to the goal model of the impacted stakeholder. For example in Fig. 7, the increased travel time is also modeled with an indicator. If the bridge is decommissioned, the real-life value of the indicator for increased travel time is 9 minutes, whereas in the case of the repaired bridge the real-life value is 0 minutes. The increased travel time impacts the indicator for time spent commuting from the goal model of the individual shown in Fig. 4, and is hence linked with that indicator. In other words, increased travel time adjusts ("+=" operator in the formula) the real-life value of the indicator for time spent commuting. Consequently, the adjusted value is now taken into account when the goal model is evaluated to reason about the actualized quality of life of the individual.

Other measurements that could be captured by the goal model in Fig. 7 are the time required to maintain the bridge (which impacts the community's potential and actualized quality of life as the community must account for this time) or the loss of fuel revenue due to shorter travel times which may impact the gas station stakeholder's potential and actualized quality of life.

As now demonstrated, all Sustainability Engineering concepts listed at the beginning of this sub-section can be captured with existing Goal Modeling approaches given the structure of the goal model described in this sub-section. While most nodes in the goal model are either coordinated with or fed directly from the proposed Sustainability Engineering approach (e.g., needs or key measurements, respectively), the links in the goal model typically represent further information not available from the Sustainability Engineering approach. These links make goal model analysis of human development possible.

The resulting goal model makes use of (i) standard Goal Modeling features such as stakeholders, goal hierarchies, and satisfaction evaluation, (ii) some rather advanced features such as indicators and formula-based indicators, and (iii) the new concept of time indicators. However, for the evaluation of the goal model to accurately reflect the development and the community, dynamic conversion functions are also required as described in the following paragraphs.

Dynamic Conversion Functions. There are some indicators for which no *best*, *threshold*, and *worst* parameters have yet been defined – namely the time indicators in Fig. 4, which also contribute to the indicator for the potential quality of life in Fig. 5. Since the indicators impact goal model elements in Fig. 4, a conversion function must be specified, so that a satisfaction value can be calculated that is subsequently used in the evaluation of the higher-level goal model elements in Fig. 4. The inclusion of time measurements is central to GOES. Therefore, it is necessary to interpret real-life time data as accurately as possible in the goal model. At this point, however, it is not specified how the real-life values of these indicators are to be converted into satisfaction values that can then be propagated to the connected tasks and eventually help assess actualized quality of life. However, conversion functions have been defined for other indicators in the goal model. What is the difference between these indicators? The indicator for potential quality of life in Fig. 5 has universally agreed-upon *best*, *threshold*, and *worst* parameters. They are the same for any stakeholder. The indicators for the sustainability indices in Fig. 6 have a *threshold* parameter that is universally agreed-upon and *best* and *worst* parameters that are determined by the stakeholder to which the indicators belong and are largely independent of the goal model. In general, this is how Goal Modeling techniques handle these conversion parameters. They are determined independently from the goal model.

However, this is not sufficient for the indicators in Fig. 4. Considering the indicator for time spent resting, who is the source of its *best*, *threshold*, and *worst* parameters? One could argue that it is the individual who decides what the appropriate parameters are for herself/himself. However, that does not reflect reality very well. Other stakeholders do have an influence on these parameters. For example, general suggestions may exist from medical associations for minimum rest times and the individual's doctor may have additional recommendations based on the current health state of the individual. Considering the indicator for time spent commuting, this is dependent on the choice of work location and even on infrastructure improvements that may reduce travel time. As another example, consider the indicator for the time spent taking care of children. This indicator is dependent on whether the children are going to day care or not. Therefore, a *threshold* that is set for the case where children are going to day care is vastly different than the *threshold* for the case where children stay at home.

Consequently, the *best*, *threshold*, and *worst* parameters are dynamically dependent on other stakeholders and other decisions made either by the individual or other stakeholders, i.e., the parameters depend on something that should also be modeled in the sustainability goal model. A correct conversion function is fundamental to the correct evaluation of the goal model. Therefore, dynamic adaptation of conversion functions is needed to adjust the parameters accordingly. Note that the *threshold* parameter is most likely to be dependent, while the other two often can be determined universally due to physical limitations (e.g., resting for 0 minutes a day is obviously the *worst* parameter while commuting for 0 minutes a day is the *best* parameter).

An example influence on a *threshold* parameter is modeled for the indicator of time spent taking care of children in Fig. 8. The default *threshold* is set at 6hrs per day. Depending on a decision of the individual to send a child to daycare or keep the child at home (modeled with two tasks), the *threshold* needs to be adjusted for the indicator related to the time spent taking care of children. If a child is at daycare, then the *threshold* has to decrease (–2hrs), while the *threshold* increases if the child stays at home (+7hrs) (SV in the formula stands for satisfaction value and ensures that the correct adjustment is made when a task is selected, i.e., SV = 100, or not selected, i.e., SV = 0). The adjusted *threshold* can then be taken into account during the analysis of the goal model in Fig. 4 (e.g., a real-life value of 8hrs is assessed differently based on the adjusted threshold and propagated upwards accordingly).

Dynamic conversion functions require a change to the URN metamodel, i.e., an Enumeration attribute of the Contribution metaclass indicates if the contribution targets the indicator or the *best*, *threshold*, or *worst* parameter of the conversion function. In addition, the evaluation algorithm needs to account for incoming links that do not change the satisfaction value or real-life value of the indicator, but instead influence the *best*, *threshold*, or *worst* parameters of the conversion function. These incremental changes to the evaluation algorithm provide goal models with a novel, fundamental ability to reason about stakeholders and their decisions more explicitly and quantitatively, as is required for GOES.

In summary, it is now possible to introduce time cost into the goal model (a) as a parallel, quantitative evaluation criteria to the generic satisfaction evaluation and (b) as more precise input to the goal model evaluation of actualized quality of life. Time indicators determine the scope of this evaluation. Within this scope, real-life time cost values are used instead of generic satisfaction values. The generic and time cost evaluations, however, are not fully disjoint. Some indicators are used in both, e.g., those time indicators that are connected to other time indicators and tasks (see the time indicator for time spent commuting in Fig. 4 and Fig. 5). In this case, the real-life values of the indicator are converted into satisfaction values for contributions towards tasks and real-life values are used for contributions towards other time indicators. The proposed structure of the goal model, hence, allows the dual analysis of potential and actualized quality of life of multiple stakeholders.

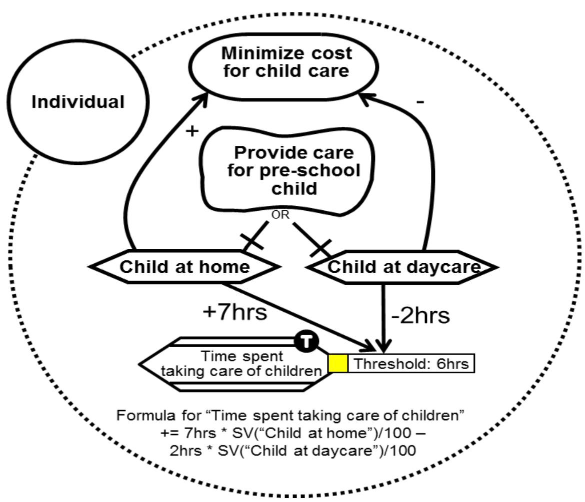

Fig. 8. Influencing the Threshold of Indicators.

VI. Related Work

Goal Modeling has been applied to sustainability, e.g., to capture requirements for more sustainable conferences [5][20] or for a software application that aids in living a sustainable lifestyle [16], to help discover sustainability requirements for an event management system [14], or to capture sustainability goals of a university [26]. A systematic literature review on sustainability in software engineering [21] does not cover any further, applicable goal modeling examples. To the best of our knowledge, there is no prior work that combines a quantitative Sustainability Engineering approach with a qualitative Goal Modeling approach based on time cost to assess quality of life for stakeholders and sustainability of a development. GOES aims to provide the foundation for such a combination.

A lot of research in requirements or software engineering and sustainability focuses on making software engineering, the software industry, and software products more sustainable [2][23], by (i) advocating the inclusion of sustainability into the list of software qualities to be considered from early development phases on, (ii) providing a reference model for sustainable software engineering [15], or (iii) suggesting definitions of sustainability in the context of software engineering [18]. In contrast to the research cited in this paragraph, the focus of GOES is slightly different as it suggests using goal-oriented requirements techniques in conjunction with a quantitative Sustainability Engineering approach to help assess broader-scoped development projects that do not necessarily have to be software related.

Others promote greater emphasis on the social dimension of sustainability [12], but have not yet provided concrete modeling approaches in support of such emphasis. GOES intends to address social needs by assessing quality of life for a variety of stakeholders. A complementary, generic model for sustainability [19] could be used to inform the goal model hierarchy in GOES, but would have to be merged with the specific needs covered by GOES and its indicators based on time cost. Another area of research that could be combined with GOES is the estimation of resource consumption based on scenario descriptions [10]. GOES is built on URN which integrates goal models with a scenario-based language that could be used for that purpose. Last but not least, there exist research streams into energy efficient cloud computing or similar that are related to sustainability and software engineering but quite orthogonal to the work described here.

VII. Conclusions and Future Work

This paper presents *Goal-oriented Engineering for Sustainability (GOES)*, a novel method combining a Sustainability Engineering approach and a Goal Modeling approach, to assess technological and human development in concert to reason about potential and actualized quality of life. The method combines detailed quantitative assessments from the Sustainability Engineering approach with high-level qualitative reasoning from the Goal Modeling approach. It is argued to convert excessive resource consumption into a *time cost* to the community based on a life cycle analysis for each alternative, thus determining the *efficiency* by which people use their time to meet their needs. Goal-oriented reasoning is then employed to determine the *effectiveness* of how people use their time to meet their needs. To this end, a sample development assessed by GOES demonstrates how key concepts of Sustainability Engineering can be modeled with goal models. The example motivates goal model extensions, i.e., *time indicators* and *dynamic conversion functions*, which allow for novel reasoning about *conversion parameters*, i.e., the parameters that regulate the conversion of real-life values into goal model values.

While goal models for sustainability will be much more complex than the didactic examples presented in this paper, the proposed structure of the goal model is still applicable to real-life situations. We envision at least three usage scenarios for GOES. In the first scenario, an engineer will use the goal model to assess the impact on representative population groups (e.g., based on statistical data for household income and time use). In the second scenario, an individual may want to tailor the goal model to her own situation to assess a proposed community development, thus fostering greater government accountability, openness, and personal involvement. In the third scenario, policy makers will use the goal model tailored to representative community groups to assess how successful incentives to improve human development may be in convincing individuals or communities to use their new-found time from a sustainable development for constructive actions instead of destructive behaviors.

In future work, the hierarchy of needs should be expanded with the aim of establishing a canonical representation, connecting low level activities to the high level goal of actualized quality of life and taking constructive and destructive actions by stakeholders into account. Such a model could then be used as a default model that is customized to a particular assessment of a development. Furthermore, it should be investigated how indicators can characterize not just leaf nodes as is currently the case but also higher level elements in the hierarchy of needs. This would require agreement on such measurements but allow quantitative assessments to be performed for larger parts of the goal model.

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