An Approach for Planning Sensor-Based Inspection of the Built Environment

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Summary

The promise of lower costs for sensors that can be used for construction inspection means that inspectors will continue to have new choices to consider in creating inspection plans. However, these emerging inspection methods can require different activities, resources, and decisions such that it can be difficult to compare the emerging methods with other methods that satisfy the same inspection needs. Furthermore, the context in which inspection is performed can significantly influence how well certain inspection methods are suited for a given set of goals for inspection. Context information, such as weather, security, and the regulatory environment, can be used to understand what information about a component should be collected and how an inspection should be performed.

The research described in this paper is aimed at developing an approach for comparing and selecting inspection plans. This approach consists of (1) refinement of given goals for inspection, if necessary, in order to address any additional information needs due to a given context and in order to reach a level of detail that can be addressed by an inspection activity; (2) development of constraints to describe how an inspection should be achieved; (3) matching of goals to available inspection methods, and generation of activities and resource plans in order to address the goals; and (4) selection of an inspection plan from among the possible plans that have been identified. The authors illustrate this approach with observations made at a local construction site.

1 Introduction

As sensor-based construction inspection becomes more cost-effective, sound investment in construction quality requires a construction site-wide identification of inspection needs, detailed planning of the inspection tasks and resources required to address these inspection needs, and decision-making assistance to make cost-effective allocations of inspection technology on construction sites (Gordon et al 2003). Current approaches for selecting inspection methods and generating inspection plans are no better than rule-of-thumb approaches without the ability to generate, evaluate, and select among multiple inspection possibilities. Sensor-based inspection methods only amplify the difficulty of planning inspections, since they may require very different approaches to inspection than their alternatives. This includes even measuring different types of attributes in order to derive the value of the desired attribute. Sensor-based inspection methods also require decisions about selection of sensors and other sensing components and their desired locations. The capability to formally generate inspection plans does not exist in a way that inspectors can compare vastly different methods that can achieve the same inspection result. As a result, choosing among inspection methods with detailed knowledge of the associated implications can not be easily achieved.

In order to support the formal generation of inspection plans, the following inspection concepts need to be represented and reasoned with. First, inspection performance goals (goal states for objects that are to be inspected, and the attributes of these objects to be inspected) must be represented in such a way that they can be refined by reasoning with inspection and context knowledge. Second, inspection constraint goals (goals that constrain how the inspection performance goals are to be achieved) must be represented in such a way that one can select inspection methods that satisfy these constraints and can be applied to satisfy inspection performance goals. Third, inspection methods must be represented in such a way that they can be matched to appropriate inspection performance goals and constraint goal domains and be used in order to generate, evaluate, and select among different inspection activities and their resource requirements. Addressing the need for formalism in this area of inspection planning permits decision-makers to generate multiple inspection options for a given inspection goal. Only at this point, one can conceive a vetted inspection plan.

2 Example

An office building currently under construction in Pittsburgh features a cast-in-place parking garage in its lowest levels. The construction sequence places the construction of an elevator core and a column line on the right side of the picture in Figure 1 on the critical path, while the construction of the column line on the left side of the figure is less constrained. The right-hand line of columns were placed and cured during December 2003, which averaged less than 40º Fahrenheit. For this project, concrete quality was evaluated based on three criteria: compressive strength, air content, and workability. Concrete strength inspection was conducted by taking samples of concrete as it was delivered to the site and then subjecting these samples to destructive compressive strength tests in a laboratory setting. Air content was tested daily for each concrete type using the pressure method outlined in ASTM C 231. Concrete was also tested daily for workability by testing concrete slump. The specifications required that non-destructive inspection methods such as sonoscope and impact hammer were not to be performed without the architect's permission, and even then not as the sole basis for approval.

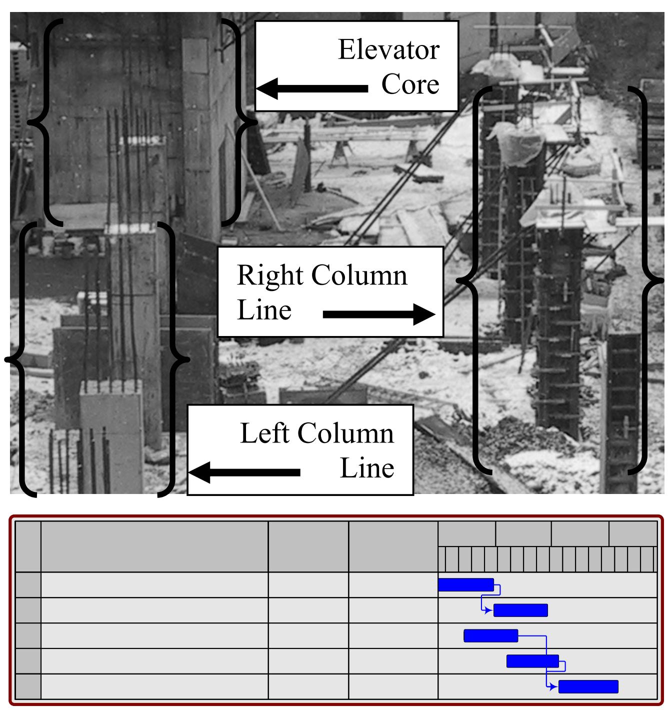

Figure 1: The left-hand line of columns was placed and cured in normal weather conditions, while the right-hand line of columns was placed and cured during cold-weather conditions. The elevator core, shown in the upper left-hand corner, was placed and cured in normal weather conditions, but was on the critical path, along with the right-hand line of columns.

In the absence of a formal inspection planning environment, it is significantly easier to make blanket ad hoc decisions about selection of inspection plans, without comparing available options. This is not necessarily optimal since this type of decision may lead to inspection plans that are not appropriate to a given context and that may not be as effective as other possible plans.

For the example above, the lack of an environment to assist inspection planning and sensing infrastructure decisions led to the use of rule-of-thumb decisions about inspection that may not in fact contribute to better schedule or quality control. The inspection goals selected did not reflect information needed due to the weather context, and some of the methods chosen for inspection possibly slowed the duration of the construction project because the minimum time taken to implement them was longer than other possible methods.

This example highlights the needs for an inspection planning approach that permits refinement of goals for inspection, context-driven matching of inspection goals and inspection methods, method-driven generation of inspection activities and resources for the object being inspected, and selection of inspection methods. The need for these items is described in further detail in the following sections.

2.1 Need for Inspection Performance Goal Refinement

This example shows that goals for inspection exist at different levels of detail. For example, i.e., the high-level goal of inspecting concrete quality can be decomposed into goals for inspection of air content, compressive strength, and workability. Therefore, inspectors may have to refine given inspection goals in order to select activities that achieve the goals. In this example, the goal of inspecting the material quality for the three sets of components led to the same breakdown of sub-goals since they are all made out of the same material. This indicates that components have context-independent inspection goals. If these goals were represented formally, it would be possible to reason with a given product model and automate the refinement of these goals.

Although typical goals may apply to a majority of construction environments, some goals for inspection that only apply in specific contexts might be overlooked without more automated reasoning. For example, in addition to the typical goals for inspection of cast-in-place concrete, cold weather conditions bring added concern about whether concrete setting is going to be affected by freezing temperatures. The right-hand line of columns was placed in a cold-weather context, which led to an additional goal for inspection requiring that concrete temperature be monitored during the curing process. Hence, an inspector needs to reason about the context in which inspection will be performed in order to further refine higher-level goals for inspection, although typical goals may apply to a majority of construction environments. In order to formalize this, inspection goals related to different inspection contexts need to be represented, and the reasoning necessary to refine goals needs to be developed.

2.2 Need for Inspection Constraint Goal Development

The example also demonstrates that contextual information can be used to guide how performance goals are to be achieved. For example, concrete may cure more slowly in cold weather conditions than under normal conditions. As a result, testing procedures that follow a strict testing schedule may be out of synch with the speed at which concrete cures (it could reach its desired strength after a 28-day sample-based testing period, at which point a sample supply may be exhausted). In this example, an inspection method requiring a shorter minimum duration is is more appropriate for the inspection task. Furthermore, in order to ensure that the concrete does not freeze, the temperature of concrete must be tested regularly. Inspection methods that test temperature discretely may miss points at which concrete may freeze and stop setting. Currently, no standards exist for how frequent such testing should be, so this constraint must be set by an inspector.

The right-hand line of columns are on the critical path (and hence are in an acceleration context). As a result, column inspections, which impact the decision to build the beams above the columns, also affect the overall duration of the construction project. The goal of inspecting concrete strength is an example of an inspection goal that impacts the decision to proceed with subsequent construction. The contractor would benefit from a measurement frequency that allows early notification when the concrete achieves its minimum acceptable strength to permit successive activities. Hence, inspection methods that require an inflexible period of evaluation, such as seven day intervals, may hold up construction progress. Some inspection methods may follow a testing schedule that may be modified by permission of the architect. Sample-based methods, such as the compressive strength testing method have such flexibility, but at the risk of destroying a finite number of samples too early.

All the components in the example are structural elements (i.e., they are in a structurally significant context), and as such are not ideal candidates for destructive testing. Hence, any inspection selected for these elements should be conducted non-destructively. In this example, workability, compressive strength, air content, and temperature goals should be addressed non-destructively.

Even with a simple example, such as the one above, it becomes evident that the manner in which inspection is to be performed must be formalized in order to develop contextually-appropriate inspection plans.

2.3 Need for Inspection Method Comparison Capability

Many methods are available to satisfy the goals above, but because they are implemented so differently, comparison of alternative methods is difficult. For example, the inspection of concrete compressive strength can be achieved by crushing concrete samples taken at the time of concrete placement or taken from the component later in its lifecycle, by monitoring temperature in situ, and by testing material properties using ex-situ sensors, such as the velocity of sonic pulses transmitted through a component. Some possible benefits may exist in reducing the complexity of inspection plans by limiting the number of inspection methods used on site. However, it is not beneficial to standardize on a limited set of methods without regard to how applicable they are to a given situation. In the example, the reasoning behind excluding non-destructive methods for testing is not transparent, possibly not even to the architect. Replacing this blanket exclusion with criteria for inclusion can permit inspection planners to consider these methods. It is possible to consider a number of other methods beyond those chosen, possibly at lower cost, higher quality, and less impact to the construction schedule.

The maturity method is an example of a sensor-based inspection method that can be applied in the example for compressive strength inspection. Such sensor-based methods require planning not only of the inspection activities required, but also of the selection and location of measurement, computation, and communication technologies needed to satisfy the goals for inspection. It is possible to use the same sensor technology to address multiple goals. This can create significant benefits, but further complicates the inspection planning process. Hence, it is possible to consider multiple options for satisfying inspection goals, but particularly in the case of sensor-based inspection methods, this requires additional planning capability and commitment.

3 Approach

The envisioned approach for planning sensor-based inspection for construction contexts consists of the refinement of inspection goals, heuristic mapping of the refined inspection goals to inspection methods by inferring how the goals are to be achieved in the inspection context, and generation, evaluation, and selection of inspection methods. The proposed approach is shown in the IDEF0 diagram shown in Figure 2.

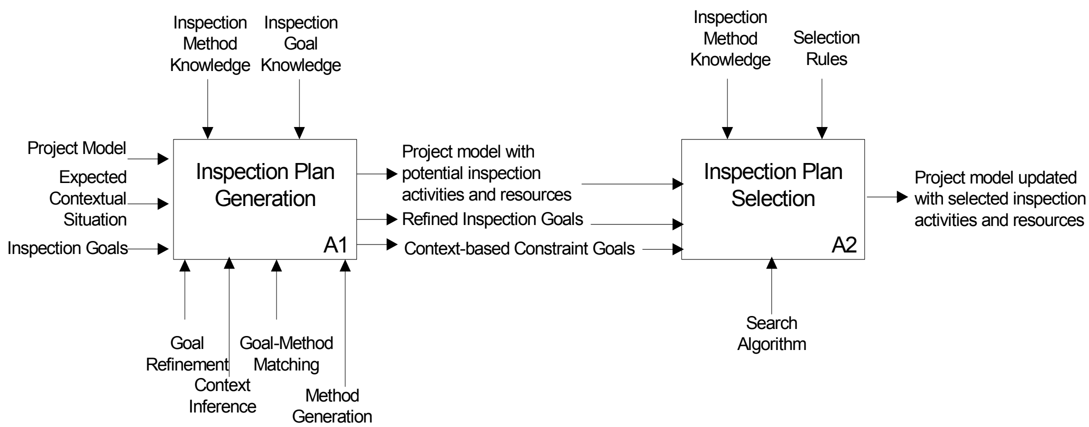

Figure 2: Reasoning with the project model, integrated with context data, inspection performance goals and constraints and knowledge about inspection methods and inspection goals, can generate many possible inspection plans for consideration before selecting and adding inspection activities and resources to the project model.

3.1 Assumptions

Given decades of research in product and process modeling, such as that described in (Froese 1999), it is reasonable to expect that it is possible to generate detailed project models. For this research, the desired level of detail for these models would be such that attributes to be inspected (for example geometric features, and typical material attributes such as strength) are either represented explicitly, can be derived, or can be added, and construction activities are integrated to the product model.

Research has been conducted for the past thirty years on representation and reasoning with specifications (Fenves 1995). It is foreseeable that one can derive goals for inspection that are linked to the project model based on a set of construction specifications (Boukamp 2004). However, the representation of inspection goals generated by this reasoning process may not be sufficient for the purpose of inspection planning, as discussed in the case above. Inspection goals may need to be refined further based on an available set of inspection methods and the contexts in which inspection will be performed.

It can be assumed as well that constraints on accuracy, precision, and appropriate time period need to be determined prior to planning an inspection, either by an inspector or other reasoning agent, and these are also assumed as given in the proposed approach.

3.2 Inspection Goal Generation and Refinement

3.2.1 Inspection Performance Goal Refinement

As shown in the example, goals for inspection can exist at multiple levels of detail and can be context-specific. In order to ensure that a given inspection goal is at a sufficient level of detail that enables inspection planning, it is necessary to first reason with information about the inspection context to determine if more detailed goals are required, and then about a set of goven inspection methods to determine if the goal can be directly achieved by those methods.

Whereas inspection of the concrete in the example presented above is limited to workability, air content, and compressive strength, inspection of underwater concrete quality includes concrete durability in the inspection goals as well (McLeisch 1994). Therefore, it is necessary to first consider the context of a component before selecting inspection activities. The inspection goal representation shown in Figure 3 shows that a context-based refinement method can be applied when initially presented with an inspection goal to query context inference rules with the time period for inspection (described in the following section), context information, such as weather conditions, and information about the object and attribute to be inspected.

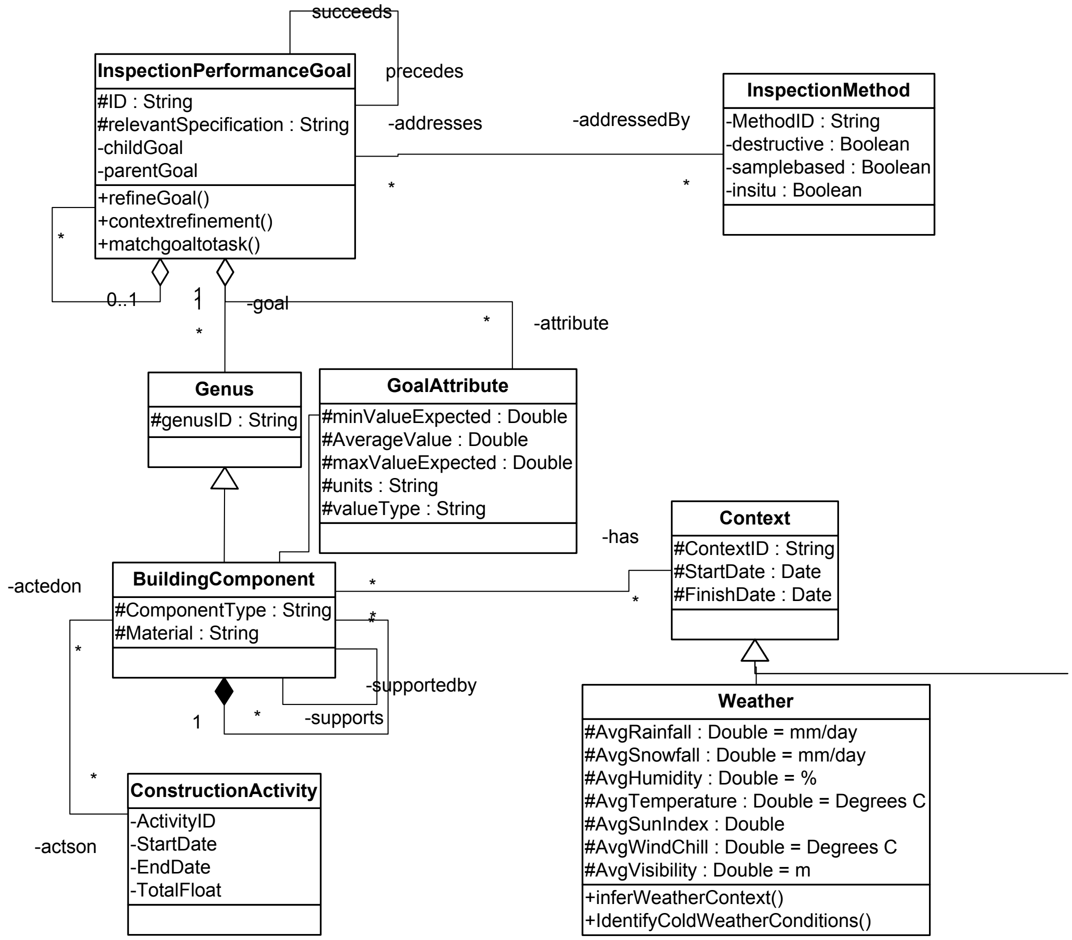

Figure 3: Inspection performance goals can be refined into sub-goals by reasoning with parent and child attributes and information about the context in which inspection will be performed.

One can refine inspection goals by reasoning with standard representations of sub-goals which always apply independent of context. For example, every instance of the goal of inspecting concrete quality can be subdivided into sub-goals of inspecting air content, workability and compressive strength. By reasoning with an inspection goal's parent and child attributes, one can match goals to sub-goals stored in a knowledge base. These goals may have logical relationships among them such as goal precedence relationships that indicate the nature or order of goal fulfillment. In addition to the standard sub-goals associated with inspection goals, inspection knowledge can be used to determine context-based sub-goals. For this example, inspection knowledge can be used to further refine the concrete quality inspection goal in the cold-weather context to include temperature monitoring.

In the example presented above, concrete columns are constructed in temperatures of less than 40º. Given the material and construction method, a context inference method can infer that the components are in a cold-weather context for this time period. Based on this context information, the context-based refinement method implemented under inspection performance goal class can be used to determine whether given inspection goals must be refined due to the inspection context. In the column example, the high-level goal of inspecting concrete quality must be refined due to the cold-weather context.

Some inspection goals may require inspection of attributes such as concrete quality that cannot directly be achieved by available inspection methods. This may be due to the fact that the attribute to be inspected is not directly measurable. In this case, the goal must be refined further.

3.2.2 Inspection Constraint Generation

The column example demonstrates that goals for inspection can indicate both what is to be inspected as well as how the inspection is to be performed. This corroborates research conducted by Sathi, who found that there are two types of goals for activities: performance goals and activity constraint goals, or goals which define how performance goals are to be achieved (Sathi 1985). These two types of goals are used to select activities that can satisfy the performance objectives and constraints.

This approach is taken to represent inspection goals, as illustrated in Figure 4. For example, the goal of inspecting concrete compressive strength is an inspection performance goal indicating what is to be inspected. This goal is associated with the inspection constraint goal of destructiveness, indicating how destructively the inspection is to be performed with respect to the object inspected.

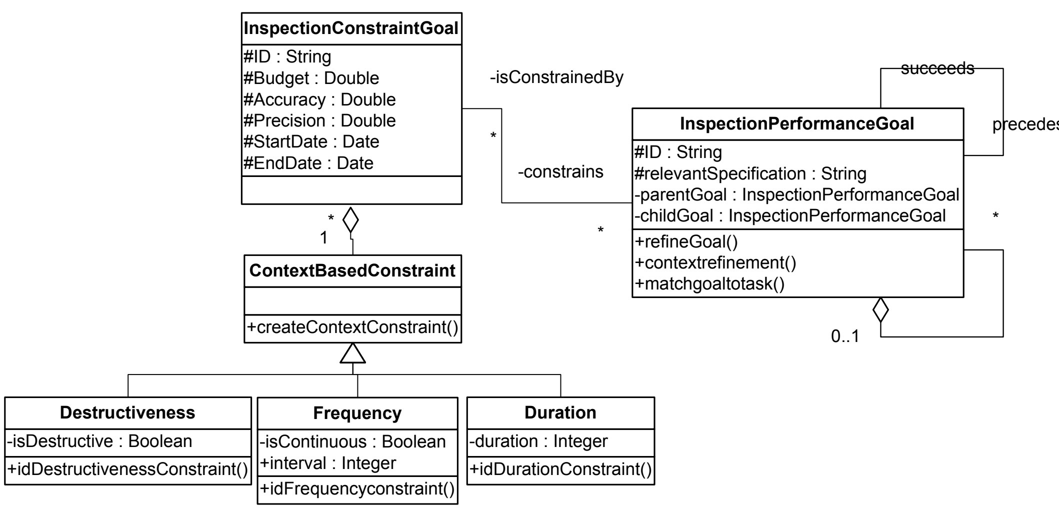

Figure 4: Inspection goals define either performance objectives or limitations on activities that address these performance objectives. Contextual information can be used to refine performance goals and add constraint goals.

A context-based reasoning method can be used to reason with context information to determine which types of constraints, such as destructiveness, frequency, and duration, are affected by given contexts. In the example, since the concrete columns were inspected in a cold-weather context, the goal of inspecting compressive strength was associated with constraints on the desired duration of activities used to address the inspection goal. Based on research conducted to date, destructivenesss, frequency, and duration appear to be general constraints on how inspection is to be performed. Further research must be conducted to identify possible other subclasses of context-based constraints. However, the proposed representation of inspection performance and constraint goals is intended to accommodate additional types of context-based constraints on inspection goals.

Additional inspection constraint goals, such as accuracy and a time period in which they can be performed, may be specified by standards or user input. Such constraints require reasoning with the process and product model or user input. For example, a component's compressive strength may be inspected only after the placement of concrete but preferably before the component supports another component. This reasoning can be used to generate constraints on start and end dates for inspection goals.

Knowledge about the attribute to be inspected in addition to the manner in which the inspection needs to be performed can be used to heuristically match inspection goals to inspection methods.

3.3 Matching of Goals and Methods

With both performance and constraint goals represented, it is then possible to match inspection goals to available inspection methods. Fischer et al. demonstrated that construction methods are appropriate within an activity domain that consists of activities to which methods can be applied (Fischer 1996). In the inspection planning work, Fischer's representation of construction methods is extended to include inspection methods consisting of inspection activities that must match both performance goals and constraint goals. By reasoning with attributes of inspection methods, it is possible to determine if methods meet performance and constraint goal requirements. For example, if the compressive strength of a concrete column is to be inspected non-destructively, finding applicable inspection methods requires searching available methods for the attribute to be inspected, the material of the object to be inspected, and the destructiveness attribute. Very different inspection methods are available for non-destructively testing the compressive strength of timber and steel components. Examples of methods that can inspect concrete compressive strength non-destructively are sample-based compressive strength method, sensor-based maturity method, and on-site rebound hammer method. Furthermore, the constraints on time period can be used to help further match goals to methods. For example, the rebound hammer test method is recommended for use on concrete that is between 7 - 90 days old (Fintel 1974). In order to determine if this method can be used to inspect the compressive strength of a column with time period constraints, one would reason with the start and end offset dates of the inspection constraint (i.e. the number of days after a construction activity associated with the inspection goal has been completed) in comparison to the offset time attributes of the available inspection methods.

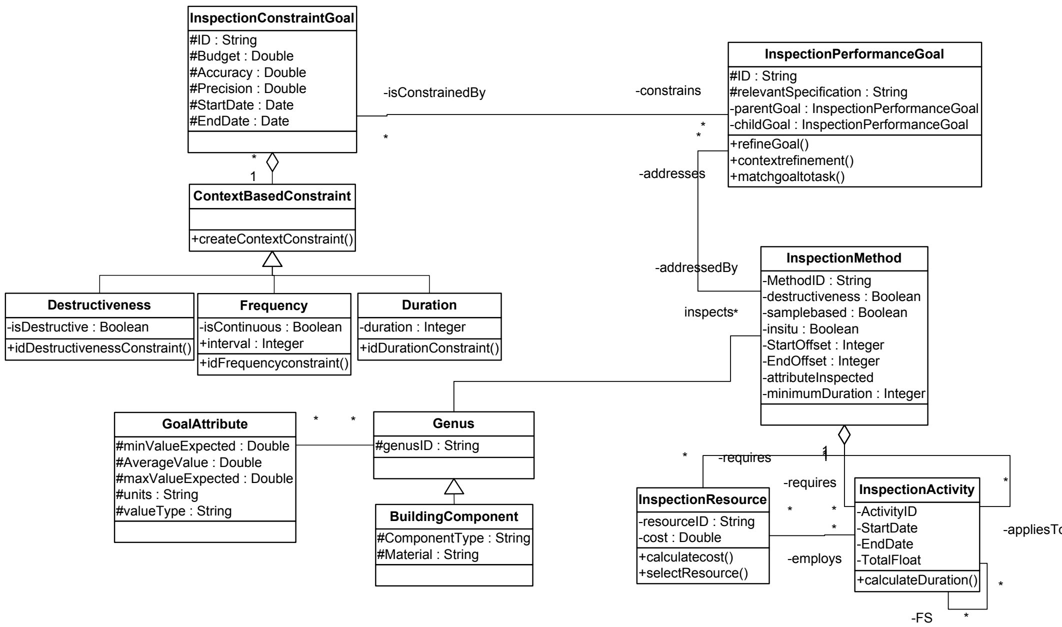

Figure 5: Inspection methods are composed of inspection resources, activities to which they apply (domain activities) activities which they require, and their logical relationships. The domain activities and attributes such as their minimum inspection time and destructivness can be reasoned with to match goals to appropriate methods.

3.4 Generation of Inspection Activities and Resources

With inspection method candidates identified heuristically, it is then possible to apply them to the existing context by using knowledge about the method to adapt their detailed task and resource requirements to the design model in order to satisfy the inspection goals. Previous research has been conducted in using construction methods to assist in planning. In Construction PLANEX, knowledge about which activities are needed to construct components are used to determine which "element activities" are required for a given design. These activities are later aggregated into "project activities". Knowledge about construction methods is used to calculate resource requirements depending on the type of activity and the anticipated duration (Hendrickson 1987). By contrast, Fischer shows that knowledge about construction methods can be used to generate plans for both resources and activities (Fischer 1996). Construction methods are represented using templates consisting of activities to which the methods apply, constituting activities, activity sequencing, constituting objects, and resource requirements. Given a higher-level activity, these templates can be used to generate lower-level activities and the type and amount of resources needed.

This approach of method-based activity and resource generation can be used to determine the types of inspection activities and resources needed for an inspection goal, and furthermore to determine the activity duration and resource quantities needed. For example, implementation of the maturity method first requires generating activities for sample collection where fifteen samples of concrete from the mix are used in order to develop the strength curve to correlate to temperature readings in the field, for the installation of temperature sensors, for temperature measurement during the curing process, and for clipping the leads at completion of inspection. The associated resource requirements are the human resources required to sample, install, read, and clip, as well as the fifteen concrete samples, cylinders, and sensing infrastructure. The amount of resources used depends on the object to be inspected and the amount of resources required based on certain features of these objects, such as determining the number of sensors required based on the volume of material.

However, sensor-based inspection methods also must be reasoned with to determine locations of sensing infrastructure within the product model and eventually the built product. Figure 6 demonstrates that instances of inspection resources, such as inspectors, inspection consumables, and sensor systems, may have different measures and means of calculating their costs and durations when applied to a given inspection object, or genus. Similarly, sensor systems and their components may have subclass-specific means of calculating their locations. Sensor systems may be packaged as a single unit, in which case their location can be calculated using a single method, or they may be separated into sensing, power, computation, communication, and memory components, each with their own location requirements.

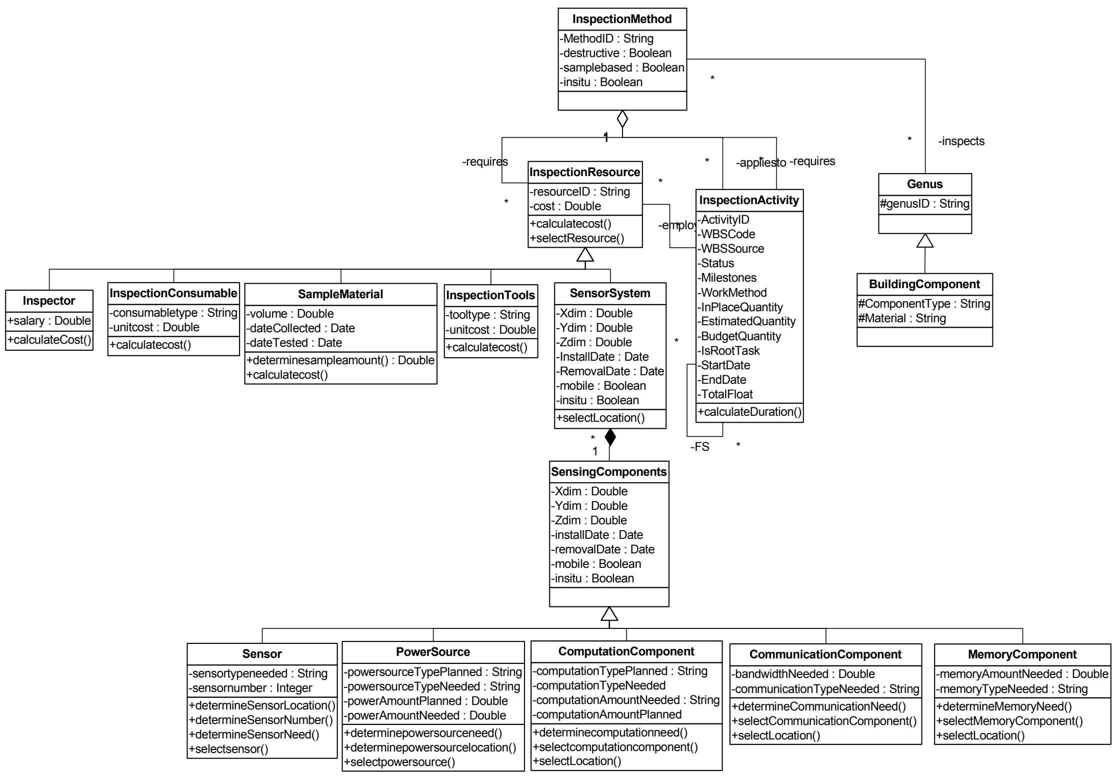

Figure 6: Methods can reason with inspection method knowledge and with features of the object to be inspected in order to calculate cost, duration, and location of inspection resources and activities.

As sensor-based inspection is an emerging area in construction inspection, standards that are currently being developed for sensor placement are evolving and sometimes are contradictory, but involve core commonalities. For example, ACI Committee 228 standards for sensor placement require reasoning about column height to create three zones, and placing sensors within these zones. On top of this requirement, sensors are to be placed at minimum volume intervals. For example, one ACI rule states that a minimum of five sensor locations should exist for the first 100 cubic yards of concrete (ACI Committee 228). Texas-DOT, by contrast, is developing standards for sensor placement based on intervals of area and volume, depending on whether components are structural, pavement, or miscellaneous concrete (Lankes, 2002). Oregon-DOT has documented an evaluation of the maturity method has sensors placed at linear offsets from edge of slab (Tikalsky 2003). Since the standards for sensor placement share common features but are not fully standardized, an ontology is needed for sensor placement, from which it is possible to build rules for sensor placement. These rules will be applied depending on the regulatory context that the component is in.

3.5 Inspection Plan Selection

By generating the activity and resource requirements for multiple methods for each goal, one can form a means of comparison in order to select the best inspection plan for a goal. Once inspection methods are generated and associated with the objects to be inspected, one can assign costs and durations to the instances of inspection activities and costs to the instances of resources, and only after that start to form the basis for comparison of different inspection methods. Inspectors may make selections based on cost for example, by adding the lowest-cost instances of inspection activities and resources to the project model.

Sensing technologies further complicate the selection process by introducing interdependencies among inspection plans. For example, the goal of monitoring the concrete temperature of columns in cold-weather conditions overlaps the goal of monitoring column concrete temperature using the maturity method, meaning that the same temperature sensing infrastructure may possibly be used to achieve both goals. Further research is needed to formalize the system-level search algorithms needed to address these possible (and desirable) interdependencies.

4 Conclusion

Sensing systems require a systematic and system-level planning approach in order to create effective deployments that meet the information needs of decision-makers for the built environment. In order to create a sufficient selection of possible inspection plans, existing knowledge can be used to refine the goals and methods available, and map goals to appropriate methods. Those who make decisions based on the status of the built environment can benefit from a representation of the information goals, methods, and context that help translate their goals to a reasoned inspection infrastructure. Furthermore, such an approach permits robust search algorithms to leverage interdependencies in possible inspection plans and plan more cost-effective inspections. An environment that accomodates knowledge-based inspection planning is needed to advise effective investments in construction quality and to break down the complexity associated with inspection planning and sensing system deployments. This paper has presented an overall approach we are attempting to build to deliver such support.

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