SIGMA EXPERT SOLUTIONS LLC

PROJECT MANAGEMENT ANALYSIS PROGRAM WHITE PAPER

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Disclaimer:

This is a white paper used to propose a concept and does not represent a design calculation. The results presented are based on careful consideration of inputs, review of calculation results, and comparison with other data, but independent check and review has not been performed. Use of this information as a basis for decision making should only be made after independent verification of calculations and independent review.

Table of Contents

1. INTRODUCTION

1.1. Background on Problem

When planning large, complex, critical, or high risk projects, thorough project analysis prior to starting work has become an industry standard. The methodology is relatively consistent across industries and outlined in some detailed in the Project Management Book of Knowledge (PMBOK) and similar references. At the heart of project planning is understanding the scope, formulating it into a schedule, determining your resource requirements, and then analyzing the impact of uncertainties and risks. Many tools have been used in the industry to assist in this process.

1.1.1. Schedule and Resource Planning

Nominal schedule and resource planning has been performed for a long time in industry, and therefore the tools and processes are mature and often tailored to an industry. At their heart, they are similar, but some tools provide finer control over scheduling, resource loading, and reporting capabilities. For the tools that are most commonly available, there is a trade-off between the capability of the tools and the ease of use.

1.1.2. Uncertainty Analysis

Quantitative uncertainty analysis is a newer aspect of project planning. Uncertainties in costs are characterized based on estimation approaches, confidence in prices, etc. Therefore, cost uncertainty analysis is relatively straightforward when taken on its own. Schedule uncertainty has often been “baked in” to the nominal schedule when doing schedule planning based on experience. In a more recent trend, newly available tools have enabled planners to use nominal durations and use uncertainty inputs to determine the appropriate activity schedule durations. This process is less well understood as its application is relatively new and the tools and processes proprietary. These tools are usually built by the same companies that provide the scheduling tools and are tailored to match the inputs and outputs of those programs. Stand-alone tools can provide additional flexibility but suffer from decreased functionality due to lack of integration with the scheduling capabilities.

1.1.3. Risk Analysis

The process of documenting project risk has been well established and is based on industry agnostic methods. At a minimum, risk evaluation is performed as a qualitative assessment, where major risk drivers are analyzed independently to determine appropriate project contingency. Newly available tools provide the ability to integrate a quantitative risk analysis with a project schedule. Similar to quantitative uncertainty analyses, the tools are generally specific to the project planning software, difficult to use, and may not provide the flexibility desired.

1.2. Summary of Issues

The current software used for complex project analysis has the following limitations:

- The scheduling and resource loading capability is a separate function from the uncertainty and risk analysis portions. This means that some aspects of schedule models must be modified or simplified to ensure proper characterization during statistical analysis.
- Modeling of uncertainties and risks is generally a complex process that is hard to equate to the standard uncertainty analysis and risk planning processes.
- Monte Carlo analyses can result in unrealistic schedules being included in the sample population that either violate hard project limitations (such as funding or start dates) or result in unrealistic resource availability.
- Most simulation systems have little verifiable documentation on their capabilities and limitations, requiring specialized experience with the software to ensure they are not used beyond their verified capabilities.

1.3. Proposed Solution

The proposed solution is an integrated project planning tool that is built for the express purpose of performing uncertainty and risk analysis of project schedules. It would integrate the ease of use found in simple scheduling tools while including the flexibility of modeling required for the most complex projects. This software would bridge the gap between software that has limited capability but high usability and software with high flexibility but complex interfaces and inputs. By leveraging the data processing capabilities of modern computers and using a clean sheet approach to this problem, legacy capabilities or features no longer used can be avoided, while retaining or expanding the ability to do complex analysis by maintaining a vast store of data for analysis without intermediate simplification.

1.4. Results and Conclusions

1.4.1. Feasibility of Software

The purpose of this white paper is to determine the feasibility of creating the software described above. To prove this feasibility, a prototype version of the software is being developed using simple text driven interfaces and python scripts. This prototype software is in ongoing development, exploring the limits of capability. In its current state, this prototype is sufficiently mature to mimic most of the capability of currently available software with some enhancements or unique capabilities. The analysis portion of this document describes the work that has been done to date on the prototype, the ongoing development for the prototype, and the vision for the final product.

1.4.2. View of the Future

There are many ways that this software could provide value to industry. This use case could range from a fully delivered software product that can be used standalone, to a proprietary in-house software used by a specialty organization. Both extremes present challenges that can be overcome. If the software is provided as a standalone and distributed copy, among the challenges realized will be:

- A fully capable software package will have many features and options which may be well beyond the needs of most project planners.
- The hardware requirements for analyzing complex schedules will be extensive given the amount of data used.
- Qualified versions of the software will require regular maintenance which may be undesirable for software only used a small portion of time.
- Lack of knowledge by those that have access to the software may result in analyses that are not valid, but still used for decision making purposes.

If the software is kept only as a proprietary in-house package available only to a specialist community, among the challenges realized will be:

- Inconsistency in inputs provided to the specialist project analysis company will decrease efficiency of input and require high overhead cost for each analysis.
- There will be less industry acceptance of the results from a product they do not recognize.
- Control of output will be limited and may not be in a format that matches the requirements for project planning reports.
- Changes in the required output information will require significant cost and interaction, further impacting the planning schedule.

The proposed implementation is to provide a limited functionality distributed software package that is capable of the scheduling and resource planning of the final software described in the analysis portion of this document. The ability to generate uncertainty and risk inputs would also be provided, as well as the ability to automatically create the WBS dictionary and risk register based on those inputs. These functions cover the majority of work required for lower risk projects. For those projects that require full uncertainty and risk analysis, a data dump file from the software would be provided to a specialty company where the analysis is performed on dedicated servers. The results would be provided back as a dump file to the project planners. This dump file would be compatible with the limited functionality software for viewing all output. As an option, the results can be reviewed by project planners experience in risk and uncertainty modeling in the specialty company to determine make recommendations on modeling improvements and how to analyze results.

This has several advantages over the other two solutions:

- The distributed software will be easy to operate and similar to commonly used products, therefore not encumbering project planners with the analyses “knobs” that can cause confusion.
- Software not performing the extensive Monte Carlo analyses will not have restrictive hardware requirements.

- Only the version of the software at the specialty company would have to be qualified for certified results as all inputs are echoed as part of the output process.
- The critical portions of software operation are performed by experts in the software, minimizing the risk of invalid results or improper operation.
- Inputs are provided through an interface that ensures they are compatible with the uncertainty and risk analysis.
- Usability of the planning side interface can result in widespread adoption of the software and industry acceptance.
- Project planners will have access to all data resulting from the analysis and can select what is displayed and how it is formatted.

1.4.3. Next Steps

Each of the sections in the analysis portions presents the next steps for the prototype, and the vision for the final product. Of the coding effort, integration of a critical path algorithm is the only technically complex aspect left. The rest of the enhancements are extensions of current capability or reshuffling of data already available.

As a research effort of Sigma Expert Solutions, the prototype software has been developed by a single person and has not been independently reviewed. Advancements in the prototype discussed in the analysis portion will be implemented in a similar manner until the coding is complete and a freeze can be placed. Prior to completing the prototype phase, a test plan must be created and executed against the final version of the prototype to verify the software meets requirements and to validate the outputs. Concurrently, a software specification must be created to guide the software development process.

There is significant effort in testing the prototype, creating a software specification, and the subsequent software development project. Whether to pursue this effort beyond the point of prototype coding will be dependent on the results of the prototype development project and level of interest from external entities.

2. ANALYSIS

The analysis of this white paper is based on results of the software prototype research project currently underway. Sections below discuss the current state of the prototype, it's capabilities, additional capabilities required prior to completion of the prototype, and long term vision for the final developed software.

2.1. Description of Software

The prototype software (referred to as the prototype) consists of Python scripts organized around phases of project planning inputs and analysis steps. The prototype is organized around the following basic functions:

- **Create a schedule** – This is a non-resource loaded schedule organized by WBS and containing schedule driving activities and pertinent information. Pertinent information includes identification, durations, relationships, and constraints.
- **Resource Loading** – The generated schedule is resource loaded. User input is used to establish resourced used in the project and assigning resources and inputs to activities.
- **Uncertainty Analysis** – Uncertainty is quantified by the user for schedule and cost inputs. The controls over schedule are duration. For cost, uncertainty is either the number of units (either duration dependent or static) and cost per unit. User input also defines the number of trials to use for the Monte Carlo simulation. The program develops a set of schedules, each one representing a permutation of the nominal schedule based on the user input of uncertainty.
- **Risk Analysis** – Risk is quantified by the user as changes to existing activities. These changes can be changes in schedule durations, resource allocation, or even activity relationships. Each risk is given a probability of occurrence. The program determines for each trial whether the risk is realized (based on probability of occurrence) and its impact. Note that the risk inputs may also be subject to uncertainty (cost or schedule variability). The uncertainty informed schedules created by the uncertainty analysis are further modified to account for risks realized in each Monte Carlo trial.
- **Limitation Analysis** – The resulting schedules are compared against user defined limitations, including funding profile, scheduling constraints, and resource constraints. Where limitations are violated, the user has the choice to either reject trials that cause a violation (and be given feedback on the number of rejections and its basis) or continued use of these trials when generating probability results.
- **Sensitivity Studies** – Based on user input, individual uncertainties or risks could be isolated and the entire analysis process described above run automatically to determine how a single uncertainty or risk impacts specific project parameters.
- **Analysis Output** – The information generated by running each schedule instance individually results in a lot of data requiring comprehension. There are essentially two types of output: simulation output and trial output. Simulation output uses information from all

of the trials to determine the impact of modeling uncertainties and risks. Trial output is information from a single trial, such as schedule information, cost information, resource usage, etc.

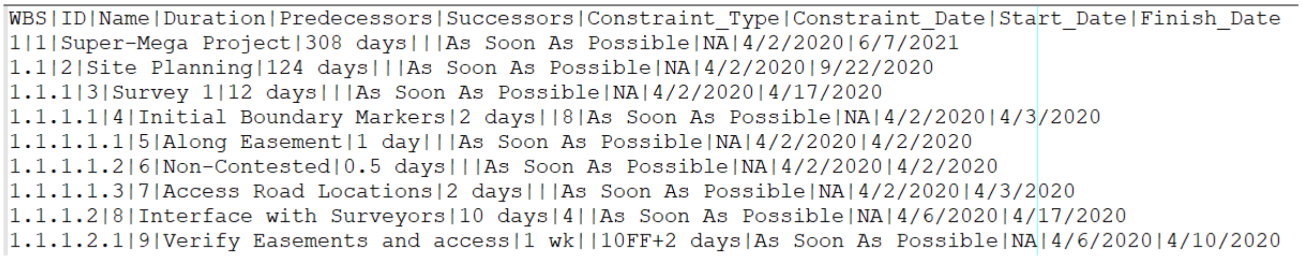
Sections following address each of these functions in more detail.

2.2. Create a Schedule

Schedule creation is the first step in project planning. Prior to consideration of resources, the nominal organization of the schedule by WBS, determining activities and relationships, and doing the initial scheduling is performed. Only after the scope is captured in the activities will resources be assigned.

2.2.1. Current State of the Prototype

In its current form, the schedule is created in Microsoft Project. Any constraint or relationship available in MS Project can be used to create the schedule. The result is then exported to a delimited file. The information exported is identifying information (task ID, WBS), duration, initial start and finish dates, relationships, and constraints. The figure below shows a part of the file generated.



```
WBS|ID|Name|Duration|Predecessors|Successors|Constraint_Type|Constraint_Date|Start_Date|Finish_Date
1|1|Super-Mega Project|308 days|||As Soon As Possible|NA|4/2/2020|6/7/2021
1.1|2|Site Planning|124 days|||As Soon As Possible|NA|4/2/2020|9/22/2020
1.1.1|3|Survey 1|12 days|||As Soon As Possible|NA|4/2/2020|4/17/2020
1.1.1.1|4|Initial Boundary Markers|2 days||8|As Soon As Possible|NA|4/2/2020|4/3/2020
1.1.1.1.1|5|Along Easement|1 day|||As Soon As Possible|NA|4/2/2020|4/2/2020
1.1.1.1.2|6|Non-Contested|0.5 days|||As Soon As Possible|NA|4/2/2020|4/2/2020
1.1.1.1.3|7|Access Road Locations|2 days|||As Soon As Possible|NA|4/2/2020|4/3/2020
1.1.1.2|8|Interface with Surveyors|10 days|4||As Soon As Possible|NA|4/6/2020|4/17/2020
1.1.1.2.1|9|Verify Easements and access|1 wk||10FF+2 days|As Soon As Possible|NA|4/6/2020|4/10/2020
```

The prototype is capable of reading this information, and rescheduling the project dates with its own algorithms, taking all constraints and relationships into consideration. Limited verification testing has shown that the prototype consistently duplicates the scheduling results of the commercially available software when all available relationships and constraints are used.

The prototype removes all non-schedule driving activities (summary activities in this case) and tracks them separately. This provides the flexibility of adding summary activities that are not part of the WBS structure for purposes of future tracking or resource loading. This is an extension of the scheduling capabilities of MS Project, but an option available in other software packages.

2.2.2. Prototype Next Steps

The prototype can determine the critical path length in its current form, but the algorithm is slow and inefficient, making integration with Monte Carlo simulation difficult to justify. Total float for individual activities is already incorporated in the software, but the results are not available for output. Future iterations will revamp the critical path algorithm and determine every path possible through the project with the amount of float available to each. This provides more detailed insight into the limiting activities of the project.

2.2.3. Developed Software Goals

The developed software will have its own user interface similar to that in Microsoft Project for schedule input. It will allow for real-time scheduling when building a schedule, independent of external programs. The ability to import from external sources will still be provided.

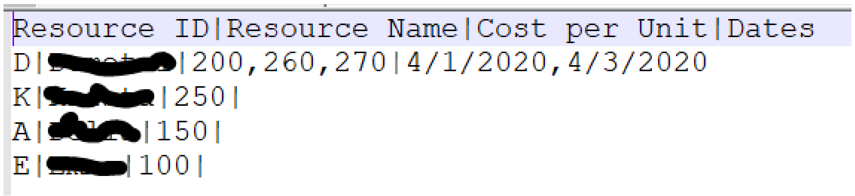
Critical path calculations will also be performed in real time, providing float for activities, a list of all project paths, and float available to each path with the critical activities highlighted.

2.3. Resource Loading

After the activities and their relationships have been determined, resource loading is performed. The two steps can be thought of as independent, but often the resource availability will inform schedule durations, so some iterative work between these two functions is required.

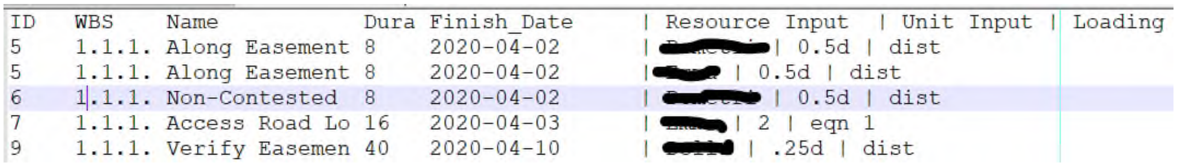
2.3.1. Current State of the Prototype

The prototype requires text file input for resource loading. The inputs are provided in three files: a resource list, a unit assignment file, and an equation file. The resource list is a delimited text file that identifies the resources, their cost per unit, and applicability dates for the cost. The applicability dates allow for providing dates where costs change (such as start of a new fiscal year). A sample of the resource list is shown below:



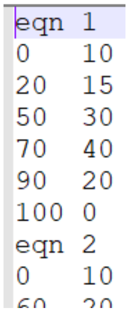
```
Resource ID|Resource Name|Cost per Unit|Dates
D|[redacted]|200,260,270|4/1/2020,4/3/2020
K|[redacted]|250|
A|[redacted]|150|
E|[redacted]|100|
```

The unit assignment file is first created by the program as output. It provides identifying information on the activities and has space available for user input. The user applies resources listed in the resource list, determines the number of units, and how the resource is loaded on the activity. The number of units can be defined based on a static number (2 units assigned to the activity regardless of duration – useful for purchasing equipment) or based on activity duration (such as .25 units per activity working hour). Loading of the resource can be performed either as distributed (even over the entire activity duration), triangular (defined by the % of the activity duration where the peak is realized), and equation driven (discussed below). A sample of the unit assignment file is shown below.



```
ID    WBS     Name           Dura Finish_Date      | Resource Input   | Unit Input | Loading
5     1.1.1. Along Easement 8    2020-04-02       |[redacted]| 0.5d | dist
5     1.1.1. Along Easement 8    2020-04-02       |[redacted] | 0.5d | dist
6     1.1.1. Non-Contested  8    2020-04-02       | [redacted] | 0.5d | dist
7     1.1.1. Access Road Lo 16   2020-04-03       | [redacted]| 2 | eqn 1
9     1.1.1. Verify Easemen 40   2020-04-10       | [redacted] | .25d | dist
```

The equation input file is used in various functional areas of the program, but in general allows a user to define an equation "shape" to be used as a profile. The profile is defined as x and y coordinates. The relative relationship between the coordinates is used, and the equation normalized, resulting in a unitless multiplier. In the case of resources, it provides the shape for unit loading on the activity, where the maximum value of the x coordinates is 100% of the duration (with other x values scaled accordingly) and the overall "height" of the profile is scaled so that the integral of the provided equation is a single unit. A sample of the equation input is provided below. In the input shown, the user chose the percentage of activity duration for the x and relative values of effort for the y values.



```
eqn 1
0   10
20  15
50  30
70  40
90  20
100 0
eqn 2
0   10
60  20
```

2.3.2. Prototype Next Steps

For the prototype, little additional functionality is envisioned. The flexibility available for resource loading is considered fully functional. Additional inputs not directly associated with resource loading will be added for use in other calculations. The first addition will be a resource limitation field in the resource list for use when performing resource leveling or rejection due to overallocation of resources. This may also include the ability to assign time periods of resource limitations and availability. The second additional input will be a maximum funding profile for the project defined similarly to the equation input described above.

2.3.3. Developed Software Goals

The developed software will have a user interface that allows for much easier population of resource lists, assignment of resources, and input of equations. The ability to copy and paste resources, loading profiles, units, etc. between activities will be provided via "fill down", copy and paste functions, or pre-defined assignments for selected activities. The ability to import resource assignments from external software will also be provided, where some manual user intervention may be required to ensure resources are properly associated with activities.

The user interface will be integrated with the scheduling function so the user can see resource usage and project cost profile in real-time during schedule development. Some tools to assist in manual resource leveling will be provided, such as the ability to view a resource loading profile superimposed on the schedule. The level of automatic resource leveling available in current products will be avoided as it often results in uncontrollable outcomes.

2.4. Uncertainty Analysis

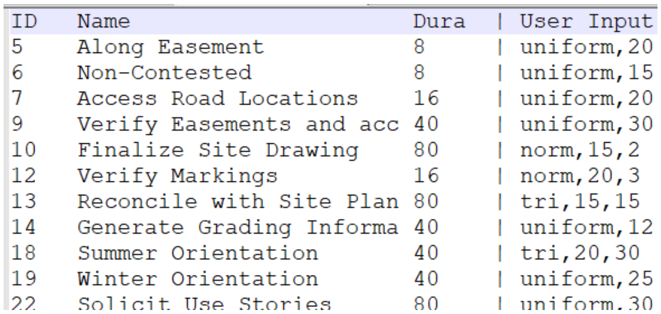
Uncertainty is the first instance where the prototype performs Monte Carlo simulations. A nominal resource loaded schedule is used as the starting point and copied for the number of trials selected by the user. Then each schedule is individually altered according to user uncertainty inputs.

2.4.1. Current State of the Prototype

The prototype uses text file inputs for the uncertainty analysis inputs. The text files are for three types of uncertainties: schedule uncertainties, cost uncertainties, and resource uncertainties. The manner of input is similar and is based on uncertainty of a certain value and the way the uncertainty should be modeled. Each type of uncertainty is described separately below.

Schedule Uncertainties

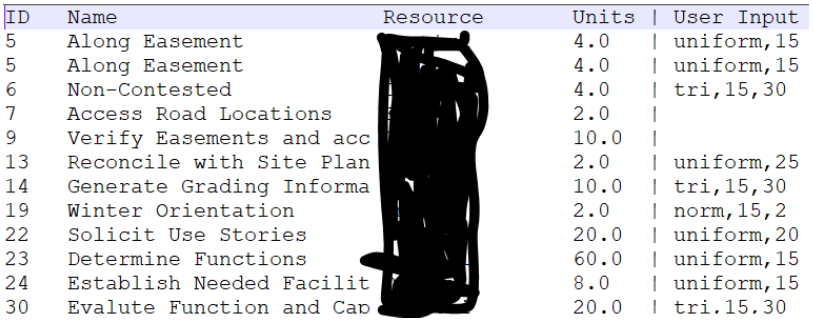
Schedule uncertainties pertain only to uncertainty in activity duration. The text file is initially created by the program where activity identification and nominal duration is provided. User input defines the uncertainty of the duration and how it is modeled. For example, in the figure shown below, Task #5 has a 20% uncertainty, where the probability of being at either end of that range is uniformly distributed (just as likely to be -18% as -2%). Alternatively, Task #10 has the probability of being away from the nominal governed by a normal distribution, which in this case says that 15% variability is 2 standard deviations from the mean. Also available to the user is a triangular distribution where the user defines the upper and lower bounds of the distribution.



```
ID   Name                    Dura  | User Input
5    Along Easement          8     | uniform,20
6    Non-Contested           8     | uniform,15
7    Access Road Locations   16    | uniform,20
9    Verify Easements and acc 40   | uniform,30
10   Finalize Site Drawing   80    | norm,15,2
12   Verify Markings         16    | norm,20,3
13   Reconcile with Site Plan 80   | tri,15,15
14   Generate Grading Informa 40   | uniform,12
18   Summer Orientation      40    | tri,20,30
19   Winter Orientation      40    | uniform,25
22   Solicit Use Stories     80    | uniform,30
```

Cost Uncertainties

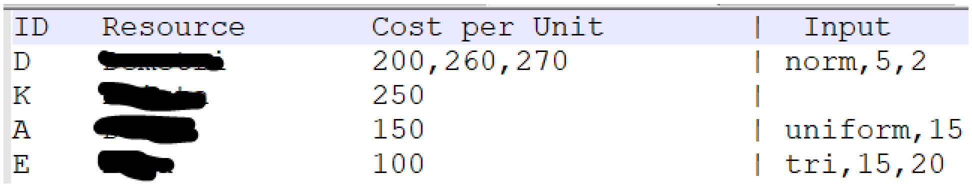
Cost uncertainties are similar to schedule uncertainties, but only impact the unit loading for the activity. As unit loading can be dependent on schedule durations, schedule duration uncertainty is calculated first prior to calculating cost uncertainties. Note that in this case, the variability is a percentage of the nominal definition of units, not the nominal units. For example, a 20% variability of a duration dependent unit load will be based on the updated duration of the activity based on schedule uncertainties, not 20% variability of the nominally assigned units. Also note that every resource allocation is addressed separately, so cost variability for one type of resource can be separated from another, even within the same activity. The figure below shows the input file used. The same distributions available for schedule uncertainty are available for unit uncertainty.



ID	Name	Resource	Units	User Input
5	Along Easement	[redacted]	4.0	uniform,15
5	Along Easement	[redacted]	4.0	uniform,15
6	Non-Contested	[redacted]	4.0	tri,15,30
7	Access Road Locations	[redacted]	2.0	
9	Verify Easements and acc	[redacted]	10.0	
13	Reconcile with Site Plan	[redacted]	2.0	uniform,25
14	Generate Grading Informa	[redacted]	10.0	tri,15,30
19	Winter Orientation	[redacted]	2.0	norm,15,2
22	Solicit Use Stories	[redacted]	20.0	uniform,20
23	Determine Functions	[redacted]	60.0	uniform,15
24	Establish Needed Facilit	[redacted]	8.0	uniform,15
30	Evalute Function and Cap	[redacted]	20.0	tri,15,30

Resource Uncertainty

Resource uncertainty input is similar to the inputs shown above. It is applied to the resource list and indicates the percentage change that may occur in cost per unit. A sample of the input is shown below.



ID	Resource	Cost per Unit	Input
D	[redacted]	200,260,270	norm,5,2
K	[redacted]	250	
A	[redacted]	150	uniform,15
E	[redacted]	100	tri,15,20

2.4.2. Prototype Next Steps

The next steps for the prototype are to provide the ability for uncertainties in limitations, as well as additional modeling flexibility. Inputs for project funding limitation is not provided, but once available, will be subject to a similar uncertainty analysis. Each trial of the schedule will be associated with an uncertainty based funding profile for comparison. Similarly, resource availability will be subject to uncertainty analysis.

The current application of the distributed function assumes the variability is centered on the nominal value. The ability to provide a different top and bottom bound would be valuable and will be implemented in the next phase. For additional flexibility, the ability to use user defined functions as a way to distribute uncertainty may be integrated. The capability may not be necessary, but could be implemented as a proof of concept.

The ability to correlate uncertainties may also be explored. There may be work-arounds for cost uncertainties (such as modeling the risk at the resource level and using the same resource everywhere) but for schedule it would be more difficult. Creating uncertainties that move together may provide value when modeling activities that would be impacted in the same way.

2.4.3. Developed Software Goals

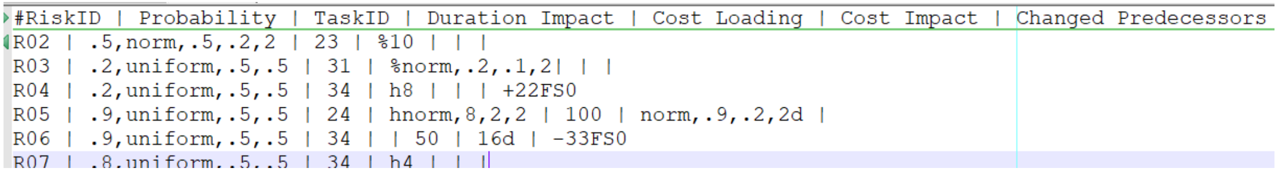
The developed software would use a user interface similar in style to the text file tabulated inputs, but with a graphical table providing drop down and fill down functions to facilitate speed of input. Each activity, resource allocation, and resource rate could be individually customized. For ease of use, the ability to establish a "standard" uncertainty for selected groups of inputs would significantly reduce workload and should be part of the developed software. Additional inputs, such as those for limitations will require a user interface as well. Those are more schedule based, so an interface that allows for input of uncertainty as a function of time would be more valuable.

2.5. Risk Analysis

Risk analysis is focused on the modeling approach, and only uses a subset of the information created during risk planning. Specifically, risk events, their probability, and consequences are input, but mitigations, and secondary risks are assumed included in the model as different inputs.

2.5.1. Current State of the Prototype

Risks are provided as input through a text file that identifies the risks and how they impact a specific activity. The risk input essentially defines the probability of a risk occurrence, what task it impacts, and how that task is impacted, either in schedule duration, cost, or change in relationships. A sample of the risk input file is shown below. Explanation of some of the more complicated fields follows the graphic.



```
#RiskID | Probability | TaskID | Duration Impact | Cost Loading | Cost Impact | Changed Predecessors
R02 | .5,norm,.5,.2,2 | 23 | %10 | | |
R03 | .2,uniform,.5,.5 | 31 | %norm,.2,.1,2| | |
R04 | .2,uniform,.5,.5 | 34 | h8 | | | +22FS0
R05 | .9,uniform,.5,.5 | 24 | hnorm,8,2,2 | 100 | norm,.9,.2,2d |
R06 | .9,uniform,.5,.5 | 34 | | 50 | 16d | -33FS0
R07 | .8,uniform,.5,.5 | 34 | h4 | | |
```

Probability of a risk is in decimal percent and can be evaluated over various distributions. For example, the probability of a risk may be most likely 50%, but decreasingly likely to occur 20% of the time. This is difficult to understand but can best be thought of as an uncertainty in knowledge of the probability. For that reason, the uncertainty distributions discussed in the previous section are available as the input. In most cases the uniform distribution would be used, which is the most common way to think of risk probability.

The duration impact can be input in one of three ways: a direct addition of duration, a straight percentage change to the activity duration, or an additional uncertainty in the duration of the activity. All three examples are shown above, represented by Risk #04, Risk #02, and Risk #03 respectively.

Similar to resource loading, unit assignment determines the activity cost risk. The input combines the capabilities of the resource loading section (units determined either static or duration dependent with assigned unit loading profile) and uncertainty input (deviation from nominal input based on various distributions). Refer to those sections for additional information.

The changed predecessors input allows a user to add or remove predecessors from an activity. Note that an activity may have multiple risks that have an impact on predecessors creating conflicts which must be addressed during the analysis.

2.5.2. Prototype Next Steps

The risks captured by the prototype thus far relate to activity based risks. There are the most common and comprise the majority of the quantified risks during project planning. The results of these risks is generally used to inform project contingency. The prototype will be expanded beyond these types of risks to enable modeling of date based risks, such as those that could be weather related or funding profiles. This allows for quantification of external risks to inform management reserve. As currently devised, one limitation is that a schedule activity must exist for a risk to be assigned. This may not be significant as the prototype allows for generation of independent summary activities which can house the risk.

Similar to uncertainties, the need to correlate risks will also be explored. This would tie the probability of occurrence of two risks together. In additional, all other enhancements planned for the uncertainty analysis (relating to modeling flexibility) would be applicable for risk as the same python scripts are used.

2.5.3. Developed Software Goals

The developed software would not expand the capability significantly, but the user interface would be something more akin to a risk register. The ability to use the project risk register as both a direct input into the analysis as well as a document that can be used by the project team would significantly reduce workload and increase the probability of using both tools. Alternatively a simple user interface for maintaining a risk database, including information not captured in the model, such as mitigation strategies, owners, etc., could be used to generate a final risk plan automatically and provide the project team an easily maintained risk database.

2.6. Limitation Analysis

All projects are faced by limitations, whether it's funding, resource availability, or pre-determined dates for activities. The ability to incorporate these types of limitations in project planning ensure that "real" simulations are used to inform project progression. It is also valuable for the planner to know how likely violation of these limitations may occur if the project is executed as planned.

2.6.1. Current State of the Prototype

The current form of the prototype does not check for limitations. The scheduling portion does identify constraints that cannot be met without violating relationships. In those situations, it respects the relationships and provides screen output that a constraint was not met. The other inputs are funding constraints and resource usage constraints, which are still in development. Therefore, no work has been done to determine violation of user defined limitations.

2.6.2. Prototype Next Steps

The prototype will be updated to analyze for limitations after all of the inputs are available. The user will be able to select whether to consider constraints (remove trials that fail to meet limitations from the population) or ignore constraints. In either case, output will be provided that indicates how many trials failed due to limitations, and specific data on why they failed.

2.6.3. Developed Software Goals

The developed software will be much like the final version of the prototype in its ability to allow the user to accept or reject trials that fail to meet limitations. The interface will be graphical instead of text-based, but otherwise no additional functionality will be required.

2.7. Sensitivity Studies

The ability to determine how impactful a specific uncertainty or risk is to the project is often desired. Generally independent sensitivity studies are performed where uncertainties or risks of interest are isolated and the analysis rerun. The ability to automatically perform this process will allow for consideration of all uncertainty and risk inputs without a significant increase in workload.

2.7.1. Current State of the Prototype

The prototype has not addressed sensitivity studies. The data has been retained and the code structure is designed so iterative re-running of the uncertainty and risk portions can be performed.

2.7.2. Prototype Next Steps

The next steps are to create the scripts necessary to do sensitivity studies. This includes the capability to provide user input on what sensitivities and risks are to be used in the study. Additionally, some means of automatically gathering results from each separate sensitivity analysis is required. Current capability will be used in an iterative manner based on this user input and data gathering requirements.

2.7.3. Developed Software Goals

The developed software will provide a simple user interface to select the uncertainties and risk used. Otherwise the capability will mimic what will be provided by the final prototype.

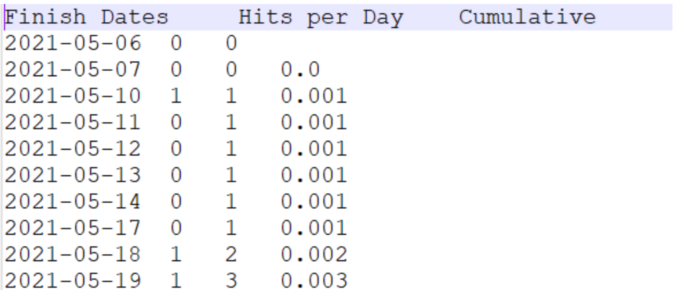
2.8. Analysis Output

Without output, the analysis performs no useful function. A means of displaying the vast amount of data generated by previous functions is necessary so that the results can be reviewed and used for project planning decisions.

2.8.1. Current State of the Prototype

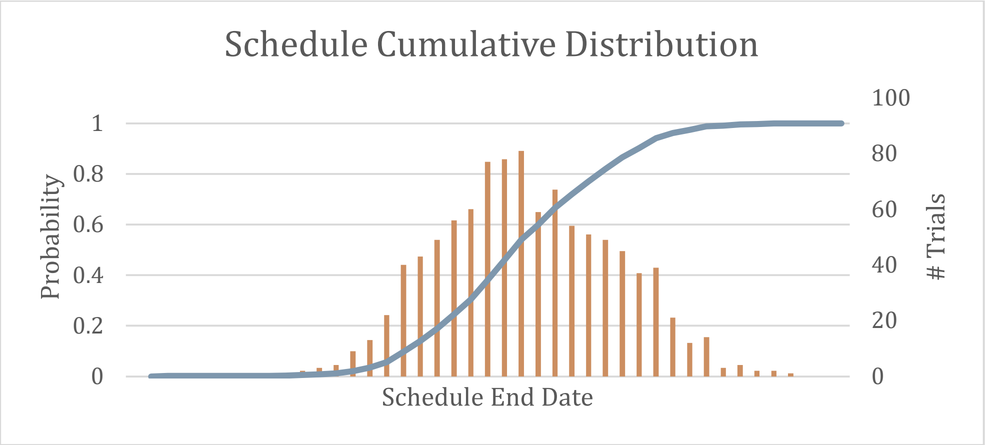
The prototype generates output by combining the results from all the simulations as well as output specific to only one trial of the simulation. The former is termed simulation output and the latter trial output.

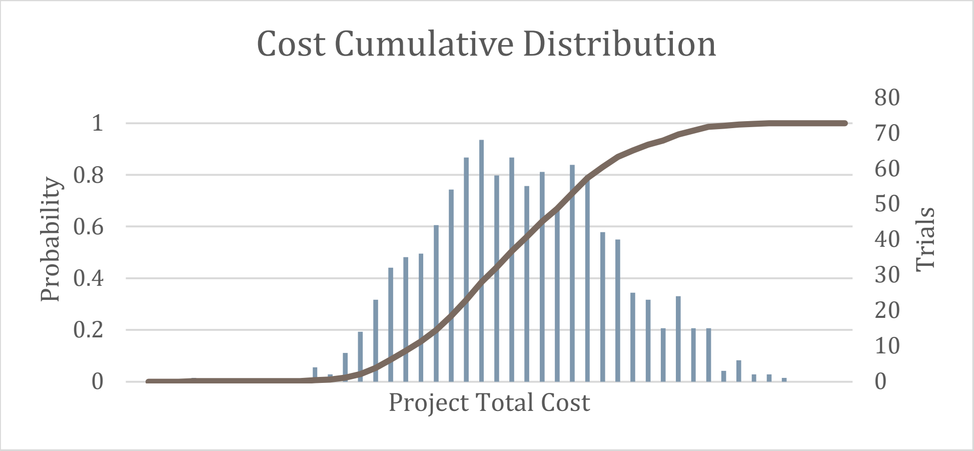
The most common simulation output is the cumulative distribution of project end date or total project cost. The prototype generates a delimited text file with this information. The results are sorted and "binned" to determine the number of trials within a bin. A sample of the output text file is shown below.



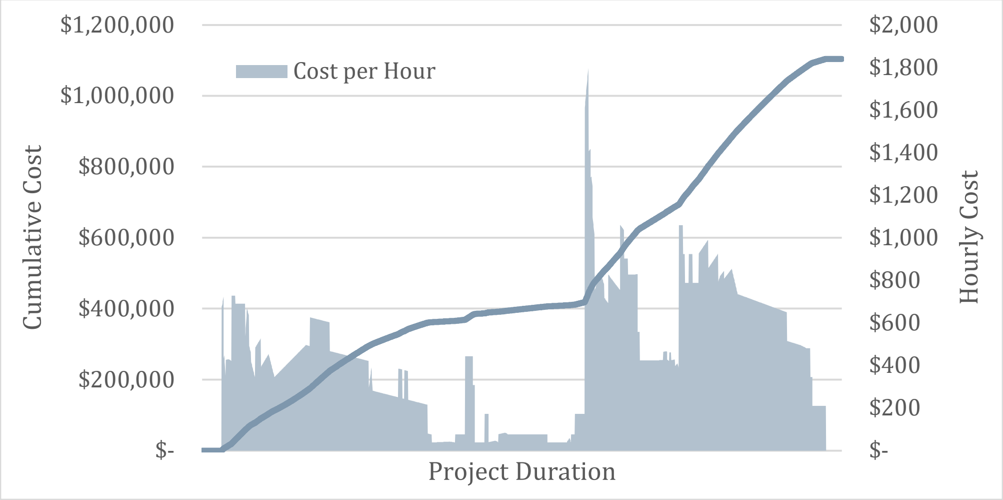
```
Finish Dates       Hits per Day    Cumulative
2021-05-06  0   0
2021-05-07  0   0   0.0
2021-05-10  1   1   0.001
2021-05-11  0   1   0.001
2021-05-12  0   1   0.001
2021-05-13  0   1   0.001
2021-05-14  0   1   0.001
2021-05-17  0   1   0.001
2021-05-18  1   2   0.002
2021-05-19  1   3   0.003
```

The data is then plotted using Excel and looks like the figures below. These figures were generated with a schedule having approximately 200 activities where approximately 70% of them had uncertainties and there were seven included risks. 1000 trials were performed to generate the data shown.

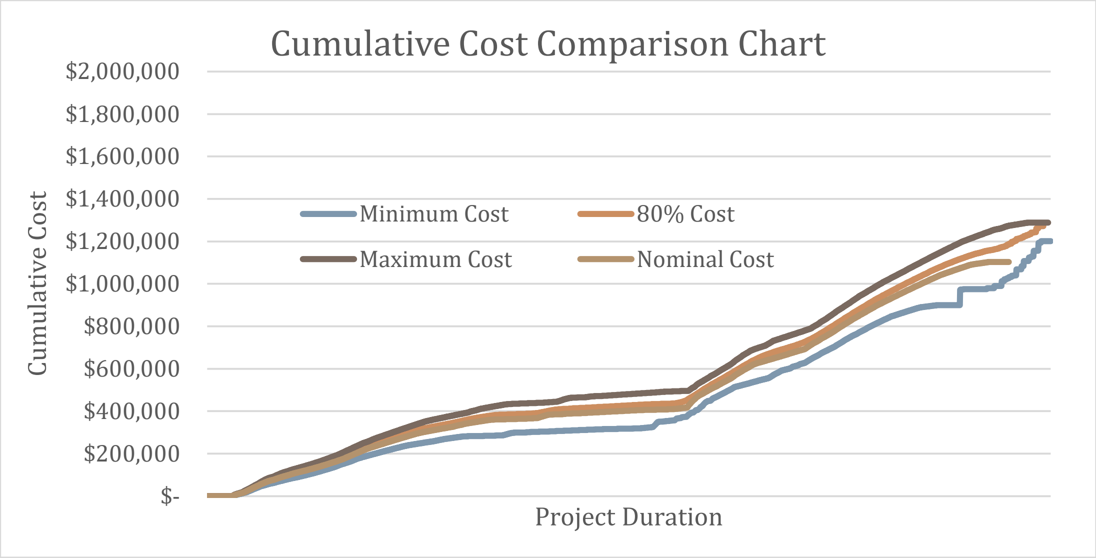




The most common trial output is the cost profile for the project. The prototype can generate this plot, as shown in the figure below for the nominal project input of the same project used in the statistical plots. Any one of the simulations can be used to generate this plot.



The last plot that the prototype can develop is a hybrid plot similar to the trial plot for cost profile. It is a cost profile for a certain percentile result. In the plot below, at each hour of the project, the cumulative cost for every trial was gathered and the lowest, highest, and 80% result was plotted. The nominal project cost was superimposed for comparison. This is not a plot typically generated, but combined with a funding profile, it could lead to some insight on whether additional funding should be pursued. It represents the potential value of retaining all simulation data in a structure where it can be easily queried and re-arranged.



2.8.2. Prototype Next Steps

The prototype will have to create several more plots based on current capability, as well as plots based on capability still in development. In terms of current capability, the ability to choose the parameter for the simulation cumulative output other than project end date or total cost is required. Options include schedule and cost for a specific activity or WBS, or usage of a resource. For cost profiles, the ability to select a parent WBS and plot it along with the total cost will also be developed. In terms of new capability, resource allocation for a single trial and a selected resource will be plotted.

Future capability of the prototype will include the ability to reject trials based on limitations, perform critical path analyses, and perform sensitivity analyses. For the former, an output on trial rejection will be required, but will only be a text file for purposes of the prototype. For the critical path evaluation, output of all project paths, the float for the path, and the float for each activity in the path will be required in text format. For sensitivity analyses, the ability to create a tornado chart for a selection of uncertainties or risks will be required of the prototype. create a resource usage profile is required.

2.8.3. Developed Software Goals

The developed software will have plotting functionality integral to the interface where all aspects of plot generation can be controlled. All plots noted for the prototype will be generated, with additional functionality in selecting what data to include in the plots.

An aspect not covered at all by the prototype is the ability to plot the schedule in various formats. For a trial, schedule output will be similar to most Gantt schedules. The ability to plot a schedule with “error bars” around each activity (similar to the layered cost profile) would also be possible to see where most of the schedule shift is occurring in the project.

The developed software should also be capable of echoing all inputs used for the analysis for use in reports, checking, and validation of work performed. Additionally, the formatting of the inputs (such as uncertainties, risks, etc.) would be conducive to easily building a WBS dictionary with all of the necessary elements. This allows for a single input process to create documentation that is usually duplicated manually.