Architects are always pushing the envelope to develop the next great building. As technology progresses, architectural concepts grow in complexity. What may have started as an abstract form drawing on the back of a napkin becomes subject to stringent building codes, energy requirements, and constructability. But of course, no project can be realized without the money to actually build it. Often times this results in designers adapting their original architectural vision into systems more affordable and constructible. Today’s architects rely on teams of consultants to help them through the development of their concepts. This also provides a means to roughly estimate a project’s budget and develop a reasonable design solution. However, once the project is turned over to the general contractor and eventually to specialized subcontractors, more detailed design and pricing is completed. Especially with complex projects, preliminary curtainwall budgets can be grossly underestimated, causing sacrifices later in design. By collaboratively developing design requirements, architects and curtainwall contractors should be able to jointly develop the architectural vision within the project constraints.

This paper proposes a collaborative engineering (CE) approach to curtainwall development. Often, collaborative engineering is confused with concurrent engineering. It is important to understand that in concurrent engineering, engineers work independently (sometimes opposite of one another) toward a common goal. Collaborative engineering requires that the engineers work together. Each member of the team must be a stakeholder who is fully vested in the outcome of the design process. Each one must contribute and bring an area of expertise that will fully benefit the team.

A more detailed definition of collaborative engineering can be found in the Defining Collaborative Engineering section of this paper.

A collaborative approach to curtainwall development will ensure that proper stakeholders are involved in the appropriate process of the design. It will shorten the total product development timeline while increasing the quality of the product and reducing life-cycle costs. By utilizing collaborative engineering, a new iterative process for conceptual design will be proposed. Collaborative engineering will also allow for more innovative designs to be developed and realized.
The typical practice of building development can be described by the design flow diagram and figure opposite. First, an owner has a need for a new building. The owner approaches architecture firms to develop the building concept. Architects create preliminary concepts from which the owner can select. Once the owner has selected a specific concept, the architect begins to assemble the design team, and the design flow begins. Each arrow in the figure represents a decision point, cost and constructability become a major concern. There can be major discontinuities in the different phases of design and production. For instance, gaps in the conceptual and detailed design phases can cause the optimized design to be greatly compromised. Once the conceptual design is finished, there is no returning to it. If changes must be made, the original design is compromised. Another more visible example is the linear process of design can create conflicts between different phases of development. The linear process of design can create conflicts between different phases of development. The linear process of design can create conflicts between different phases of development. The linear process of design can create conflicts between different phases of development. The linear process of design can create conflicts between different phases of development. The linear process of design can create conflicts between different phases of development. The linear process of design can create conflicts between different phases of development. The linear process of design can create conflicts between different phases of development. The linear process of design can create conflicts between different phases of development. The linear process of design can create conflicts between different phases of development. The linear process of design can create conflicts between different phases of development. The linear process of design can create conflicts between different phases of development. The linear process of design can create conflicts between different phases of development.
Collaborative engineering is a process of multi-stakeholder stakeholders working together to develop a common product, outcome or goal. The stakeholders may be of differing backgrounds with conflicting interests, yet a common objective must be achieved. The interactions of the MSC problem must be systematically managed in order to clearly address the problem. A stakeholder is anyone who has a vested interest in the outcome of the project being developed. Among others, this includes several different types of engineers with different specializations, managers, customers, contractors and any other person that has an interest in the developmental outcome of a collaborative project. After the organization has a clear assignment and a collection of stakeholders, the collaborative process can begin.

Multiple representations of a stack (left), including a two-dimensional section (right), and an assembled stack (center), and an exploded view of the rendering showing internal connections (right).

FIGURE 5

Since both major problems in collaborative engineering entail the same multi-attribute decision structure, they are both bound by limitations of social decision theory. Engineering problems are typically not considered as existing within social theory, but there is no avoiding it in collaborative engineering. One of the more interesting (and most challenging) social theories is Arrow’s Impossibility Theorem.

Essentially this theory states that it is impossible for a group to make a rational decision if they have the following attributes: democ- racy, independent alternatives, consistency, and an unrestricted domain. On the surface, this suggests that there is no way to collaboratively fulfill a problem’s requirements; however, there is hope for collaborative engineering. Arrow’s theory only holds true if all four limitations are met, but engineering problems never exist in an unrestricted domain. There are always limitations that restrict the domain of available alternatives (solutions) – cost, schedule, regulations, etc. By restricting the domain to reasonably available alternatives, it becomes possible to make a sound, rational collaborative engineering decision.

It is important to note that collaborative engineering is a social theory problem, and that it is possible to make a rational decision in a group setting. Since the collaborative teams contain stakeholder with conflicting interests described under Conflict Interests in Typical Practice of Curtainwall Design, we need to draw on social theory to help manage the social interactions. It is also important that we understand that the only thing that makes a rational group decision possible is the restricted domain. If collaborative teams get too caught up in examining every possible alternative, the process cannot succeed.

As stated earlier, this paper divides the collaborative engineering framework into two major problems: Multi-Stakeholder Choice and Multi-Criteria Evaluation. MSC problems represent a teamwork, while MCE problems address task-work. However, these two problems rely on the organization for the problem definition and the stakeholder assembly. The organization must set an assignment or high level goal for the collaborative engineering team. Then they must assemble a team of stakeholders to identify decision opportunities. For this to happen, there must be a clear input, a defined process, and an observable output. In this case, the input is the group of stakeholders and the defined assignment or high level goal. The stakeholders must identify their differing perspectives toward the issue and begin to create propositions or possibilities to solving the problem. Basically, this is an attempt to assess what is more important to the group and to what degree something is preferred – “is this more important than that”. By restricting the domain to only viable alternatives, weighted ranking becomes possible. Note that if for some reason a collective rationality cannot be reached, the entire process must be repeated until the team can align their perspectives with the goal and achieve a rational set of objectives that are agreed upon by all stakeholders.

When a collective rationality is achieved, the teamwork (MCE portion) of collaborative engineering is nearly complete. The team must now create a set of objectives that corresponds to the different alternatives and a set of criteria to evaluate their progress. The stakeholders must set their objectives to align with the overarching goal and their own personal expertise. The team must also develop evaluation criteria. Otherwise, any attempt to evaluate the overall utility of the team’s different alternatives is useless. After the team has set clearly defined objectives and evaluation criteria, the MSC portion of collaborative engineering is complete.

MULTI-CRITERIA EVALUATION PROBLEM

The second phase of collaborative engineering in the MCE process, as referred to as struct- tive optimization. This problem is the tradi- tional approach to engineering problems. However, in the realm of collaborative engineering, we are able to create a more systematic approach to solving complex
problems. Also, by creating the objectives and evaluation criteria collaboratively, the MCE process gives flexibility for both more practical and more innovative designs.

MCE defines the task as a work portion of collabora-
tive engineering. The purpose is to complete the indi-
vidual tasks while meeting the context of the common
understanding developed in the previous stage.

The inputs for the MCE process are the objec-
tives, the resources, and the context from the
previous stage that can be used to judge
towards achieving. In either process,
they can engage in collaborative negotiations
process until a group rationality is reached, or

Here, the individual stakeholders will use their
expertise to complete individual objectives
that were developed in the MCE stage. The team
must dynamically collaborate both during
their task-specific responsibilities and the
multi-objective optimization to find the best
possible solution. This will result in a participa-
tive joint decision within the collaborative
engineering process. However, in

The specific framework above provides a method
to help increase the efficiency of curtainwall
development while simultaneously providing
an opportunity to increase innovation. This
section will show how the specific steps and
tasks necessary in curtainwall development can
progress within the collaborative framework.

CONCEPT SELECTION &
OVERARCHING REQUIREMENTS

For the purpose of this paper, we will assume
that the overarching building type and require-
ments have already been set, and an architect-
ural concept has been agreed upon. This is to
say that the owner has already done his or her
work and that the architect must retain profit
margin while working within a finite budget.
However, there is no direct to this concern. As long as all the stakeholders
understand that conflicting interests exist and address them up front, the collabora-
tive process can proceed.

Additionally, in the traditional approach, a curtainwall contractor may receive architectural drawings complete with detail specifi-
cations. The contractor is then left to examine the drawings himself, which could lead to misinter-
pretation and specification error. The result may make an assumption to try to make their bid more competitive, but that might compromise their chances of selection due to a deviation from the architectural intent. Ensuring all consultants have a say in the entire design proc-
ses for all parties. There should remain varying perspectives throughout the entire collabora-
tive process. The next section will show how to manage these varying perspectives in a system-
atric approach.

MANGING SOCIAL INTERACtIONS

Now that the team is assembled, specific goals
and objectives for this stage must be determined
using the MEC process. As described previously
in Defining Collaborative Engineering this is a

Table 1: Sample curtainwall design stakeholders.

```
<table>
<thead>
<tr>
<th>STAKEHOLDER</th>
<th>EXPERTISE</th>
<th>PERSPECTIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owner Representative</td>
<td>owner needs / limitations</td>
<td>budget and overall project</td>
</tr>
<tr>
<td>Architect</td>
<td>architectural and overall building design</td>
<td>most innovative / creative</td>
</tr>
<tr>
<td>General Contractor</td>
<td>managing entire project</td>
<td>construction</td>
</tr>
<tr>
<td>Consultant</td>
<td>overall curtain wall design and requirements</td>
<td>architect’s vision priority</td>
</tr>
<tr>
<td>Curtainwall Designer</td>
<td>curtain wall design and construction</td>
<td>design and cost / schedule</td>
</tr>
<tr>
<td>Structural Engineer</td>
<td>curtain wall structural engineer</td>
<td>system complies with structure</td>
</tr>
<tr>
<td>Building Structural Engineer</td>
<td>building structural engineer / in-depth knowledge of project structural</td>
<td>curtain wall loads to structure</td>
</tr>
<tr>
<td>Building Mechanical Engineer</td>
<td>building mechanical systems expert / in-depth knowledge of systems structural</td>
<td>ensure adequate mechanical</td>
</tr>
<tr>
<td>Acoustics Engineer</td>
<td>acoustic engineering expert</td>
<td>ensure building meets acoustical requirements</td>
</tr>
</tbody>
</table>
```

One of the stakeholders with expertise to complete individual objectives
that were developed in the MCE stage. The team
must dynamically collaborate both during
their task-specific responsibilities and the
multi-objective optimization to find the best
possible solution. This will result in a participa-
tive joint decision within the collaborative
engineering process. However, in
many cases multi-objective optimization is not
possible. The team can either repeat the MCE
process until a group rationality is reached, or
they can engage in collaborative negotiations
to attain a sufficient solution. In either process,
these clear evaluation criteria (developed in the
previous stage) that can be used to judge
towards achieving. In either process,
there can engage in collaborative negotiations
process until a group rationality is reached, or

The table shows the diversity of the stakeholders and their complementary expertise, showing that
they bring a certain perspective to the development of the system structural
layer to accommodate thicker and heavier glass.

Additionally, in the traditional approach, a curtainwall contractor may receive architectural drawings complete with detail specifi-
cations. The contractor is then left to examine the drawings himself, which could lead to misinter-
pretation and specification error. The result may make an assumption to try to make their bid more competitive, but that might compromise their chances of selection due to a deviation from the architectural intent. Ensuring all consultants have a say in the entire design proc-
ses for all parties. There should remain varying perspectives throughout the entire collabora-
tive process. The next section will show how to manage these varying perspectives in a system-
atric approach.

MANGING SOCIAL INTERACtIONS

Now that the team is assembled, specific goals
and objectives for this stage must be determined
using the MEC process. As described previously
in Defining Collaborative Engineering this is a

Table 1: Sample curtainwall design stakeholders.

```
<table>
<thead>
<tr>
<th>STAKEHOLDER</th>
<th>EXPERTISE</th>
<th>PERSPECTIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owner Representative</td>
<td>owner needs / limitations</td>
<td>budget and overall project</td>
</tr>
<tr>
<td>Architect</td>
<td>architectural and overall building design</td>
<td>most innovative / creative</td>
</tr>
<tr>
<td>General Contractor</td>
<td>managing entire project</td>
<td>construction</td>
</tr>
<tr>
<td>Consultant</td>
<td>overall curtain wall design and requirements</td>
<td>architect’s vision priority</td>
</tr>
<tr>
<td>Curtainwall Designer</td>
<td>curtain wall design and construction</td>
<td>design and cost / schedule</td>
</tr>
<tr>
<td>Structural Engineer</td>
<td>curtain wall structural engineer</td>
<td>system complies with structure</td>
</tr>
<tr>
<td>Building Structural Engineer</td>
<td>building structural engineer / in-depth knowledge of project structural</td>
<td>curtain wall loads to structure</td>
</tr>
<tr>
<td>Building Mechanical Engineer</td>
<td>building mechanical systems expert / in-depth knowledge of systems structural</td>
<td>ensure adequate mechanical</td>
</tr>
<tr>
<td>Acoustics Engineer</td>
<td>acoustic engineering expert</td>
<td>ensure building meets acoustical requirements</td>
</tr>
</tbody>
</table>
```

One of the stakeholders with expertise to complete individual objectives
that were developed in the MCE stage. The team
must dynamically collaborate both during
their task-specific responsibilities and the
multi-objective optimization to find the best
possible solution. This will result in a participa-
tive joint decision within the collaborative
engineering process. However, in

The table shows the diversity of the stakeholders and their complementary expertise, showing that
they bring a certain perspective to the development of the system structural
layer to accommodate thicker and heavier glass.

Additionally, in the traditional approach, a curtainwall contractor may receive architectural drawings complete with detail specifi-
cations. The contractor is then left to examine the drawings himself, which could lead to misinter-
pretation and specification error. The result may make an assumption to try to make their bid more competitive, but that might compromise their chances of selection due to a deviation from the architectural intent. Ensuring all consultants have a say in the entire design proc-
ses for all parties. There should remain varying perspectives throughout the entire collabora-
tive process. The next section will show how to manage these varying perspectives in a system-
atric approach.

MANGING SOCIAL INTERACtIONS

Now that the team is assembled, specific goals
and objectives for this stage must be determined
using the MEC process. As described previously
in Defining Collaborative Engineering this is a

Table 1: Sample curtainwall design stakeholders.

```
<table>
<thead>
<tr>
<th>STAKEHOLDER</th>
<th>EXPERTISE</th>
<th>PERSPECTIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owner Representative</td>
<td>owner needs / limitations</td>
<td>budget and overall project</td>
</tr>
<tr>
<td>Architect</td>
<td>architectural and overall building design</td>
<td>most innovative / creative</td>
</tr>
<tr>
<td>General Contractor</td>
<td>managing entire project</td>
<td>construction</td>
</tr>
<tr>
<td>Consultant</td>
<td>overall curtain wall design and requirements</td>
<td>architect’s vision priority</td>
</tr>
<tr>
<td>Curtainwall Designer</td>
<td>curtain wall design and construction</td>
<td>design and cost / schedule</td>
</tr>
<tr>
<td>Structural Engineer</td>
<td>curtain wall structural engineer</td>
<td>system complies with structure</td>
</tr>
<tr>
<td>Building Structural Engineer</td>
<td>building structural engineer / in-depth knowledge of project structural</td>
<td>curtain wall loads to structure</td>
</tr>
<tr>
<td>Building Mechanical Engineer</td>
<td>building mechanical systems expert / in-depth knowledge of systems structural</td>
<td>ensure adequate mechanical</td>
</tr>
<tr>
<td>Acoustics Engineer</td>
<td>acoustic engineering expert</td>
<td>ensure building meets acoustical requirements</td>
</tr>
</tbody>
</table>
```

One of the stakeholders with expertise to complete individual objectives
that were developed in the MCE stage. The team
must dynamically collaborate both during
their task-specific responsibilities and the
multi-objective optimization to find the best
possible solution. This will result in a participa-
tive joint decision within the collaborative
engineering process. However, in

The table shows the diversity of the stakeholders and their complementary expertise, showing that
they bring a certain perspective to the development of the system structural
layer to accommodate thicker and heavier glass.
identify as many decision opportunities as possible since these will be inputs for design process that will be employed in the MCE stage. Early in the process, the team will look at the project as a whole and look for particular areas of concentration. For instance, there may be a large atrium area that requires vision glass spanning three floors. The architects may want this area to be as transparent as possible (i.e., minimal structural support). In this situation, the architects likely have been advised by their consultants and have a solution that could work. However, now that the curtainwall contractor is involved, they can begin to offer different alternatives that may enhance the architect’s vision while actually lowering the overall cost of that portion of the project. Having all the stakeholders present at this early stage allows there to be functional discourse between parties of different perspectives. It opens the door for innovative solutions to problems that may not have been fully vetted in the early conceptual phases.

In this situation it is easy to see how the team can get caught up in focusing on the more complex areas of the project. However, they must be careful not to forget the decision opportunities that lie in the more typical portions of the project. These complex areas of the project may have been fully vetted in the early conceptual design process that will be employed in the MCE stage. Once the team has clearly defined objectives and design parameters will have been developed collaboratively.

After developing objectives for the next stage, the team must develop evaluation criteria. Again this is done differently for each different design team. They must form criteria that will allow them to measure the overall utility of different design solutions, for use in the MCE problem. Once the team has clearly defined objectives and evaluation criteria, the collaborative engineering process can progress to the MCE stage. Aluminum weight versus mullion depth and width could be the measurable criteria for the mullion example above. This is a simple example, but it shows how criteria can be developed to determine the utility of an alternative.

In the MCE problem, the team will also develop a set of criteria that will be used when certain alternatives must be taken for approval. The MCE team will simply setting a meeting two weeks out with the anticipation of making a final decision on the mullion profile for the typical curtainwall conditions. The next section shows how the team can begin to develop alternatives/solutions.

DEVELOP ALTERNATIVES

The previous section fully developed the decision opportunities for the collaborative team to have the best possible opportunity to create an innovative, practical, and well designed product. By assembling a team of vested stakeholders, the team was able to develop a rational set of decision opportunities from an understanding of project limitations. Staying with the example, the team now has a clear and quantitative understanding of the importance of different parameters for the curtainwall design (e.g., a thinner mullion profile is three times more important than the depth of the profile). Also, the team fully understands the objectives and how the task-work (MCE) phase will progress.

Stakeholders should now begin their individual task-work by completing the objectives set forth in the MCE phase. Ideally, all the task-work will be completed collaboratively, but this is impossible when working with different organizations. However, since all of the objective criteria were developed collaboratively, the individual organizations will complete their task-work with solid understanding of perspectives of all interested parties. As discussed further in The Enclos Approach, Enclos has set up its design teams with a diverse set of designers and engineers to help the task-work progress as collaboratively as possible. This helps ensure that as many stakeholders as possible are applying their personal preferences to the task-work under the context of the teams collective rationality. Again, this return to the mullion optimization example. The curtainwall designer would be developing details to make the system watertight, manufacturable, etc. However, the curtainwall designer wouldn’t be designing it alone. The designer would have a structural engineer to give minimum design parameters, such as the load required and the profile moments of inertia. The designer would also have a thermal engineer to assess the shapes for condensation and identify possible thermal paths. As individual preferences are applied to the task-work collaboratively, the team will begin to form a global rationality as their objectives near completion.

This approach allows design evolution to work to its best potential. Although not all stakeholders were present during the actual task-work completion, they collectively determined the objective and scheduled further collaborative sessions to assess alternatives. The team clearly understands the inputs to the design process, because they were formed using the job. Mullions are developed collaboratively upon completion in the MCE stage. Until the traditional approach, this framework allows for a clear understanding of the inputs, process and outputs of the curtainwall design process by all stakeholders. It also allows for a design and a design process that is specifically tailored to the specific project in work.

Although this design process is performed in a much more systematic manner, it does not guarantee that the output will be consistent for every stage in the design. In fact, in the earlier iterations, the collaborative engineering team must develop several different alternatives with different configurations and varying emphases on the most important performance parameters. This will help develop several solutions or alternatives that can be examined and selected in later iterations.

There are four possibilities at the end of the collaborative engineering process: 1. A participative joint decision (most desired) 2. Return to the beginning of the task-work (MCE) phase 3. Return to the beginning of the team-work (MCE) process (restart the entire CE process) 4. Negotiate a joint decision (results in sufficing global rationality – most common)

In earlier iterations, it may be relatively easy to the participating a participative decision, because the team is selecting several successful alternatives to be developed further. However, as the number of iterations increases, the team must narrow design alternatives until they ultimately have a final design to move on to shop drawings. In the latter iterations, it may be necessary to engage in collaborative negotiations or even repeat some of the stages. The ultimate goal is to attain group rationality, resulting in the best sufficing design.
A collaborative engineering approach to curtainwall development will improve the current practice in several major ways, including:

1. The architect does not always rely upon a curtainwall consultant to fully solve the design problem. In the collaborative approach, the problem definition is developed collaboratively, ensuring that all major stakeholders can express their perspectives toward the architectural concept. This ensures that there is an in-depth consideration given to all aspects of the curtainwall design.

2. Stakeholders expose design engineers to different levels of the developmental process, allowing the early design solutions to include considerations from all levels of production. Ultimately, this creates more synergy throughout the developmental process, creating a more streamlined process (e.g., production and installation issues considered during the design phase).

3. Allowing representatives of the owner and general contractor to be involved in the design phase. Inclusion allows these parties to be more informed when handling the coordination and cooperation networks required during the design and production phases.

4. Streamline the transition from concept to production. Successive iterations can be employed to refine concepts until the design is fully defined, allowing a smooth progression into component development and shop drawings.

5. Fully defining objectives and understanding the inputs and process of design development. Additionally, the design process will be tailored to the specific problem.

6. By allowing several solutions to be developed in earlier iterations, there is a stronger possibility for innovative designs.

**The ENCLOS Approach**

The Studios were created to keep Enclos at the forefront of curtainwall development as projects grow in scope and complexity. The Studios contain a diverse group of expertise that help the design team respond to these increasingly complex projects. Each Studio employs several senior designers that bring in-depth knowledge of curtainwall design along with a great deal of experience in past projects. There are many young architectural and industrial designers that bring new perspectives and expert knowledge in advanced architectural software. Each Studio also has devoted structural and thermal engineers, as well as engineering expertise in acoustics. This team is set up to respond to future proposals as well as engage in continuing research to advance the curtainwall industry.

The Studios were created to keep Enclos at the forefront of curtainwall development as projects grow in scope and complexity. The Studios contain a diverse group of expertise that help the design team respond to these increasingly complex projects. Each Studio employs several senior designers that bring in-depth knowledge of curtainwall design along with a great deal of experience in past projects. There are many young architectural and industrial designers that bring new perspectives and expert knowledge in advanced architectural software. Each Studio also has devoted structural and thermal engineers, as well as engineering expertise in acoustics. This team is set up to respond to future proposals as well as engage in continuing research to advance the curtainwall industry. The Studios are set up to engage in a collaborative approach to curtainwall design and development. Designers are not working in a linear fashion, waiting for their designs to be reviewed by engineering. The entire team can engage in collaboration throughout the design development phase. Although it may take time for the architectural industry to fully embrace a collaborative approach, the Studios’ bid package approach to collaboratively develop these design features and mitigate some of the potential risk to project completion. The intent of design-assist is to engage in full collaboration with the owner, architect, general contractor and curtainwall contractor. This is a great opportunity to employ the collaborative process described in this paper. By approaching the design-assist phase systematically, Enclos is able to realize complex and exciting new projects.

**Conclusion**

The collaborative engineering approach to curtainwall development has several key advantages to traditional methods. While many of the examples presented in this chapter represent simple scenarios, the process can be applied to a problem of any complexity. In fact, the more complex a project becomes, the more essential the collaboration. It is easy to become focused on your particular area of expertise when looking at a complex problem, but the collaborative engineering process allows you to consider other perspectives. Ultimately, organizations have more opportunity to create more innovative, more practical, and more financially sensible products and product cycles.

Since the objectives were developed collaboratively, none of the solution alternatives should be uncollaborative development. Coordination is more preferable than others. Each iteration of collaborative engineering will refine the overarching engineering will refine the overarching goal, narrowing the design alternatives and preferable than others. Each iteration of collaboration together to solve challenges that may arise.