Pacific Northwest
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PNNL-34417

Building ControlScore: Research Laboratory Building Deployment

May 2023

Tim A Yoder
Bryan C Pamintuan
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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Summary

Improvements to building control systems can lead to energy savings and increased occupant comfort. In an optimized system, process variables such as air temperature will closely follow their desired setpoints and avoid excess energy use. Typically, experts must manually inspect individual control loops to identify poor performance and opportunities for improvement. However, this approach is difficult in modern buildings that have a prohibitively large number of controllers. To address this issue, Pacific Northwest National Laboratory (PNNL) created the ControlScore tool which captures operating data from the many controllers within a building and generates standardized scores for each loop on a scale of 0 to 10 (a score of 0 indicates poor control, a score of 10 indicates good control).

In order to test real world performance of the ControlScore and gain feedback from building operators, PNNL applied the Building ControlScore tool to all available real operational data from a laboratory building within the period of May 1, 2020, to January 1, 2023. The building scored a 5.36 overall, with all four of the building's sections scoring between 4.5 and 6.5. The scoring methods are calibrated so that the 0-10 score range roughly represents a normal distribution of building control in the real world. As such, most buildings fall near the middle of the range. Thus, these results indicate that the analyzed systems have a fair performance with moderate room for improvement. No specific type of loop was problematic, but the lowest and highest performing loops in each building section were identified.

While the ControlScore identifies loops and systems that aren't meeting their designated setpoints, it does not indicate the cause of those issues. For example, consider a supply air terminal unit's airflow loop that received a low score due to it delivering less air than specified by the setpoint. The lower-than-desired airflow could be due to equipment limitation (e.g., the terminal unit or duct serving is too small to accommodate that airflow), malfunctioning equipment (e.g., a stuck damper or bad sensor), or something else entirely. The ControlScore does not diagnose problems, it simply identifies the symptoms that can be explored and addressed by building operators. For this study, the building operators were provided with the ControlScore findings so they could investigate performance issues. The building operators also provided feedback on how the tool could be enhanced.

Acknowledgments

We would like to thank the building's Facilities and Operations team for their support in providing access to the building data and feedback on the tool design.

Acronyms and Abbreviations

CHWS	chilled water supply
CUP	central utility plant
Disch	discharge
Exh	exhaust
ID	identification
PNNL	Pacific Northwest National Laboratory
PV	process variable
SP	set point

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1.0 Introduction

This report provides an overview of Pacific Northwest National Laboratory's (PNNL's) Building ControlScore tool, including the methodology behind ControlScore, and results from deployment of the regulatory control layer of ControlScore, which includes the proximity and stability aspects of the tool applied to a real operational data set gathered from a laboratory building which will be referred to as Building A. It also includes feedback from building operators on ways the tool could be improved.

1.1 Background to Building Controls and Energy Efficiency

Modern buildings contain large numbers of feedback controllers that regulate process variables (PV) to follow the associated setpoints (SP). In this context, a PV is the thing being controlled (e.g., the actual zone temperature), and the SP is the desired target of that PV (e.g., a zone temperature setpoint). The performance of these controllers has a direct impact on occupant comfort and the overall energy use of a building. Thus, identifying poorly performing loops and systems is the first step to improving a building's control, comfort, and potentially energy efficiency metrics such as energy use intensity. Some buildings may use alarms to flag variables that cross a certain threshold, but this method is not as reliable as more sophisticated methods that analyze behavior over time and generally results in a large number of "nuisance" alarms that are often ignored by operators.

1.2 ControlScore Overview

Typically, investigating control performance requires a manual inspection of a system. Within the system of interest, the loops must be identified. For example, in a variable air volume system, each air terminal unit can have multiple control loops for airflow volume, discharge air temperature, and zone temperature. Then, the values of the PV and SP over time within that loop must be analyzed (e.g., comparing the trended histories of the actual airflow and the desired airflow). Determining the loop's control performance is not an exact and simple process. Rather, an expert must make the determination based on knowledge of the type of system. This approach may work for a few systems that have been flagged by alarms or can be identified by outlier behavior compared to similar systems in the same building, but this does not identify all the problematic loops, nor can the results be aggregated for comparison between buildings or sites. Inspection by an expert likely cannot be used for every single system in a building since modern buildings can have too many of these loops to monitor and evaluate the performance of each manually. Thus, there is a need for a more systematic, automated, and standardized method of scoring building control performance that can be applied to large datasets while avoiding prohibitively large workloads.

To address these challenges, researchers at PNNL created the ControlScore concept (Salsbury 2023). ControlScore takes operating data from the many controllers within a building and generates standardized scores for each loop on a scale of 0 to 10 (a score of 0 indicates poor control, a score of 10 indicates good control) using a probability-based measure. The scoring methodology includes three aspects of control: proximity of PV to SP, stability of PV, and comparison of SP trajectory with references.

The proximity aspect measures how closely the PV is being controlled by the SP. The distribution of points in the PV is compared to distribution of points in the SP. Figure 1 below illustrates two examples of this scoring method. The top image of Figure 1 shows an example of a PV that generally has the same value as the SP, so it receives a high score. In contrast, the bottom image in Figure 1 shows an example of a PV that is not close to the SP, so it receives a low score.

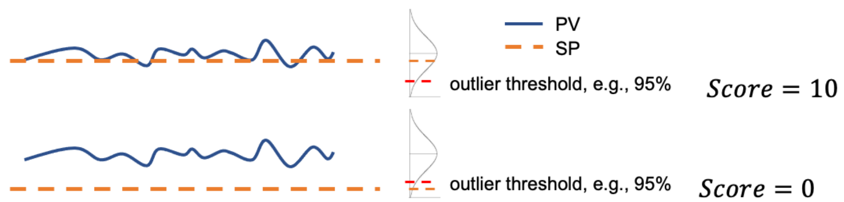

Figure 1. Proximity Aspect of ControlScore.

The stability aspect measures how the PV fluctuates around the SP over time. Figure 2 below illustrates this concept, where the oscillations in PV can be scored. This behavior is not captured in the proximity score because the average error of both signals in Figure 2 may be close to 0, but the behavior represented in the top part of the figure may indicate poor control performance.

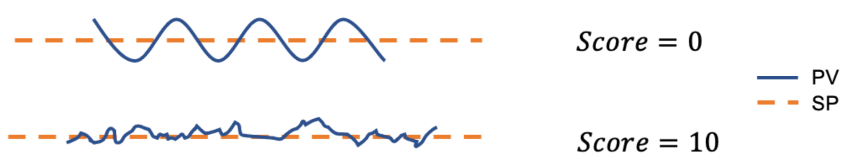

Figure 2. Stability Aspect of ControlScore

The expected trajectory aspect compares the actual SP to a reference SP that is known to be well-performing. Figure 3 illustrates this concept, where the score is a function of the distance between the actual SP and the well-performing reference.

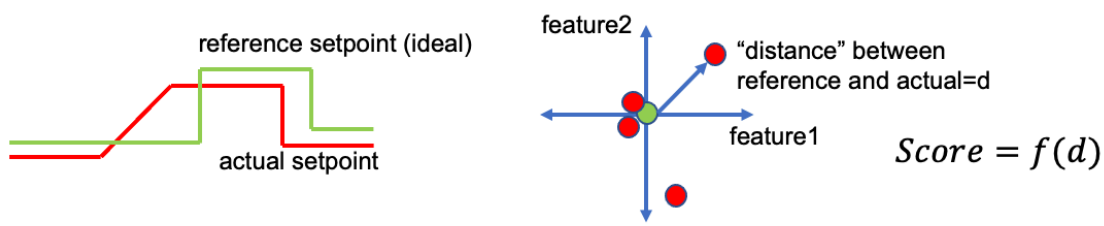

Figure 3. Trajectory Aspect of ControlScore

The regulatory control layer, which includes only the proximity and stability aspects, is the focus of this deployment of ControlScore. Supervisory control, which is the SP reference aspect, is not included in this analysis due to insufficient metadata for the loops and systems being assessed. Scores are calculated for each loop and then aggregated to the system, building, and site levels to allow for easy assessment. Calculated scores are stored in a database and accessible through a web-based user interface.

Calculating control scores requires certain data properties. The **data required** to produce a regulatory score is only the time series measurements (or trend history) of SP and the associated PV. Evaluation of the SP trajectory requires additional information. **Sample frequency** does not have a significant effect on the scoring methods as long as the dynamics of the loop are captured. However, very slow sampling may reduce the information contained in the signals and mask certain aspects of behavior, while very fast sampling may add noise. The **time span** should be monthly to both include enough samples while still showing changes over time. **Data quality** does not have a significant effect on the scoring methods, as long as there are not too many gaps or severe quantization.

2.0 Analysis

PNNL applied the Building ControlScore application to all available data from a laboratory building which will be referred to as Building A. This analysis covers two aspects of the ControlScore: proximity of the PV to the SP and stability of the PV. The data covers May 1, 2020, to January 1, 2023.

2.1 Data Available and Metadata Extraction

For this analysis, the available data came from the JCI Historian Database stored in a Microsoft SQL Server. Additional metadata on the points, their relation to physical systems, how they related to each other, etc. had to be inferred from the data in the database.

This data included a point name and the associated units of measure for 5127 different points. An example is shown below:

A.4/System 1.DISCH-AIR-TEMP

Each of these points can be categorized into a PV, SP, SP limit, or a measurement point that is irrelevant to ControlScore. This point mapping allows PVs to be matched to SPs for scoring. These points can also be grouped into their respective loops, systems, and building sections, which is used for proper matching of PVs to the correct SPs and allows aggregation of results. Ideally, this information would be modeled directly with some type of semantic model, such as one based on BrickSchema or Haystack. However, that type of metadata was not available for this analysis, so it needed to be extracted from the available data.

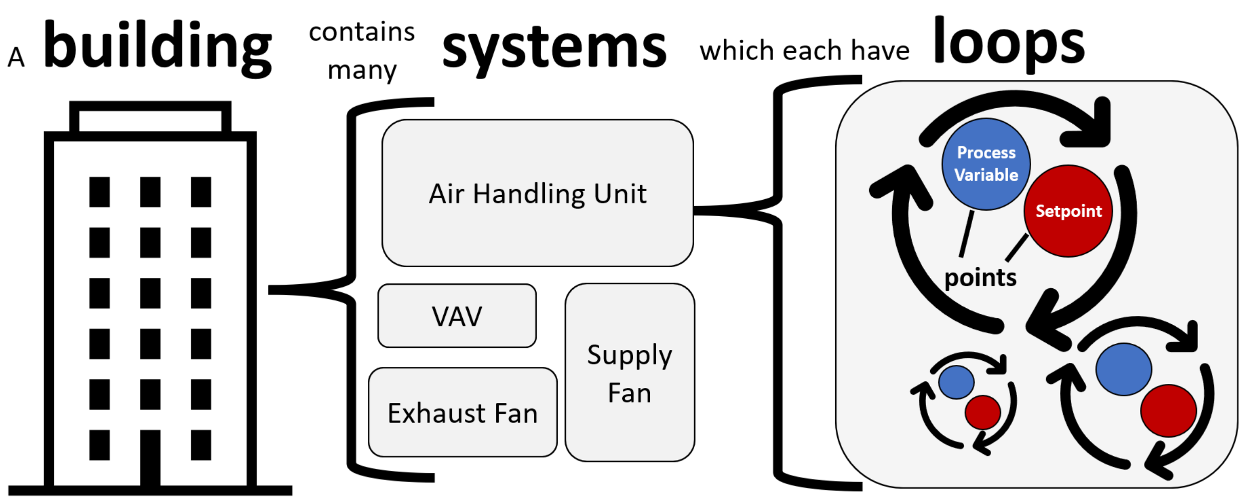

Figure 4. Hierarchy of Points, Loops, Systems, and Buildings

To do this point mapping, the necessary information was found in each data point name. Splitting up a data point resulted in three key pieces of information: building section, system name, and point name. The same information was extracted from each of the available points. An example summary for a small subset of points is shown below in Table 1.

Table 1. Information Extracted from Point Name

Full Point Name from Database	Section	System	Point
A.4/System 1.DISCH-AIR-TEMP	A.4	System 1	DISCH-AIR-TEMP
A.4/System 1.DISCH-AIR-TEMP-SETPT	A.4	System 1	DISCH-AIR-TEMP-SETPT
A.2/System 8.DISCH-AIR-TEMP	A.2	System 8	DISCH-AIR-TEMP
A.2/System 8.DISCH-AIR-TEMP-SETPT	A.2	System 8	DISCH-AIR-TEMP-SETPT

The section and system were used to group points in the same system. Then, some manual inspection was done to assign loop types. Table 1 above shows points from two different systems that each contained a DISCH-AIR-TEMP loop. Next, each point was mapped to a point type (PV or SP). An example summary is shown below in Table 2.

Table 2. Point Mapping

Section	System	Point	Loop Type	PV	SP	SP Limit
A.4	System 1	DISCH-AIR-TEMP	DISCH-AIR-TEMP	1	0	0
A.4	System 1	DISCH-AIR-TEMP-SETPT	DISCH-AIR-TEMP	0	1	0
A.2	System 8	DISCH-AIR-TEMP	DISCH-AIR-TEMP	1	0	0
A.2	System 8	DISCH-AIR-TEMP-SETPT	DISCH-AIR-TEMP	0	1	0

PV = process variable; SP = set point.

Next, identifications (IDs) were assigned to each unique section, system, loop, and point. An example subset of the point ID table is shown below in Table 3. Similar tables existed to identify the building section, system, and loop. The IDs from these tables are also shown in the point ID table below.

Table 3. Point ID

Point	Section ID	System ID	Loop ID	Point ID	PV	SP	SP Limit
DISCH-AIR-TEMP	4	204	269	1066	1	0	0
DISCH-AIR-TEMP-SETPT	4	204	269	1067	0	1	0
DISCH-AIR-TEMP	2	15	286	1229	1	0	0
DISCH-AIR-TEMP-SETPT	2	15	286	1230	0	1	0

ID = identification; PV = process variable; SP = set point.

The information from the ID tables allows each datapoint to be matched to its setpoint within the same loop and categorized into its appropriate section of the building and system. This organization allows ControlScore to identify which PV should be regulated by which SP. In Table 3 above, points 1066 and 1067 are seen to be in the same loop (as indicated by the binary PV and SP columns in Table 3); one is the PV and one is the SP. Similarly, points 1229 and 1230 are PV and SP pairs in a different loop, which is part of a different system in a different section of the building. ControlScore was able to take this metadata and compare the appropriate PV and SP pairs to generate scores (according to the methodology described in Section 1.2), then aggregate results at a system or building level.

2.2 Building A Overall Performance

The next few sections of this report will provide an overview of the results, trends, and a few examples of specific systems and loops with both high and low performance.

Analysis of the laboratory building's data resulted in an overall building control score of 5.36, which can be split into four individual section scores. Figure 5 below shows the distribution of the section scores, with all four scores falling between 4.5 and 6.5. Section A.3 scored 4.55, Section A.4 scored 5.09, Section A.1 scored 5.65, and Section A.2 scored 6.14.

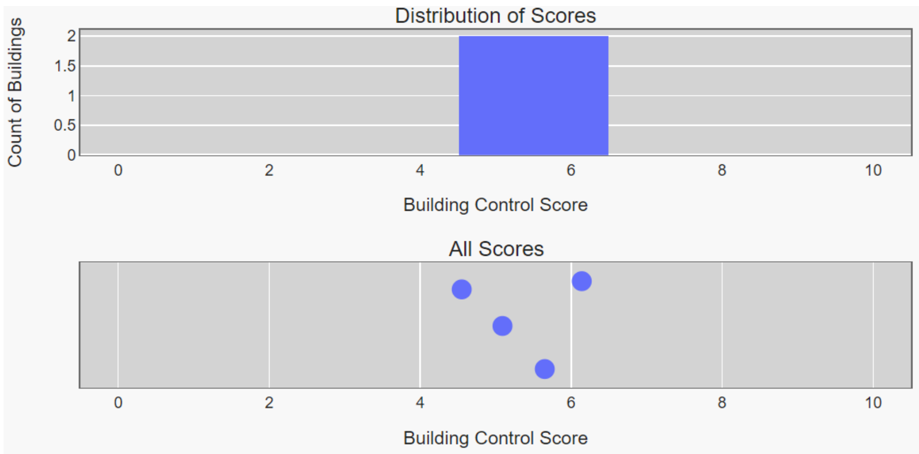

Figure 5. Distribution of Control Scores for the Four Sections of Building A

These results indicate that the building has an average performance overall with some room for improvement. Also, each of the sections has a similar level of control, with Section A.3 showing the most room for improvement.

2.3 Building Section A.1

Section A.1 scored 5.65 overall. The trend of this score over time is shown in Figure 6 below. The behavior has remained relatively stable over time, with the score never falling below 5 or rising above 8.

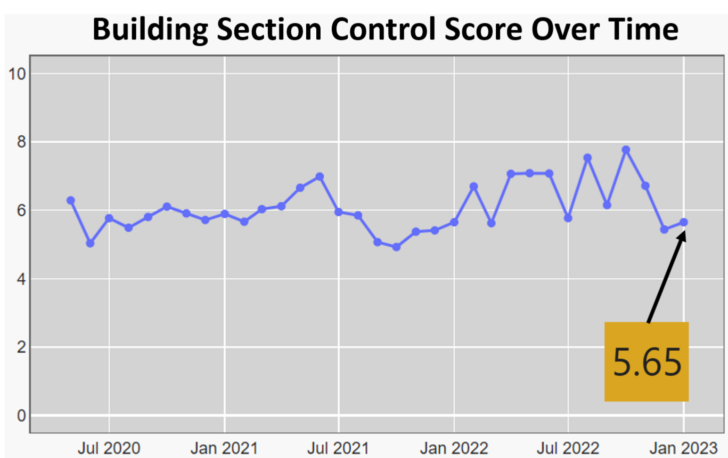

Figure 6. Section A.1 Control Scores Over Time

Section A.1 includes 24 different systems. The distribution of scores for these systems is shown in Figure 7 below. As can be seen, there are two clusters of scores: 9 systems with high performance (>7) and nine systems with low performance (<1.5). There are no identifiable characteristics that separate the high and low performing systems, as both clusters have the same types of loops (mostly supply flows). Further information and examination of the building equipment may reveal some common characteristics of poorly performing loops (e.g., found mostly in variable air volumes, found mostly in air handling units, older equipment).

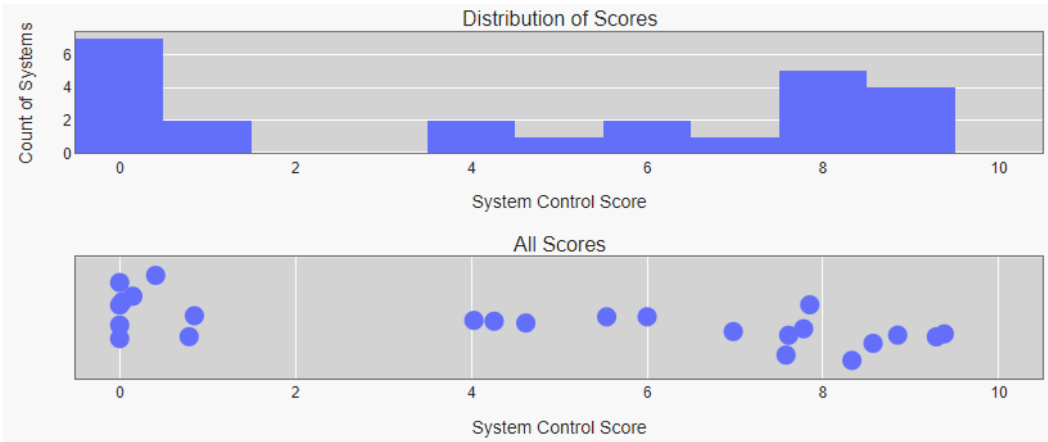

Figure 7. Distribution of System Scores within Section A.1

Table 4 below shows the systems in section A.1 with the highest 10 scores and the loops that are included in each of those systems. The maximum system score achieved is 9.38. The systems all include supply air flow loops, and half of the systems also include an exhaust flow loop.

Table 4. Section A.1: 10 Highest Scoring Systems Information

System ID	System Control Score	System Loops
138	9.38	Supply Flow
146	9.29	Exh Flow, Supply Flow
137	8.85	Exh Flow, Supply Flow
140	8.57	Supply Flow
141	8.33	Supply Flow
147	7.85	Exh Flow, Supply Flow
133	7.78	Exh Flow, Supply Flow
139	7.61	Supply Flow
142	7.58	Exh Flow, Supply Flow
138	6.98	Exh Flow, Supply Flow

Exh = exhaust; ID = identification

Figure 8 below shows the score over time and the raw data for the supply flow loop in system 138 (the only loop in the highest scoring system). The control score over time shows a sharp increase in score through the end of 2020, then a stable performance score between 8 and 10 through the end of the available data. The bottom left figure shows the raw time series data with the supply flow setpoint in red and the supply air flow process variable in blue. The air flow seems to track the setpoint well and remains relatively stable, resulting in a high 9.38 loop control score.

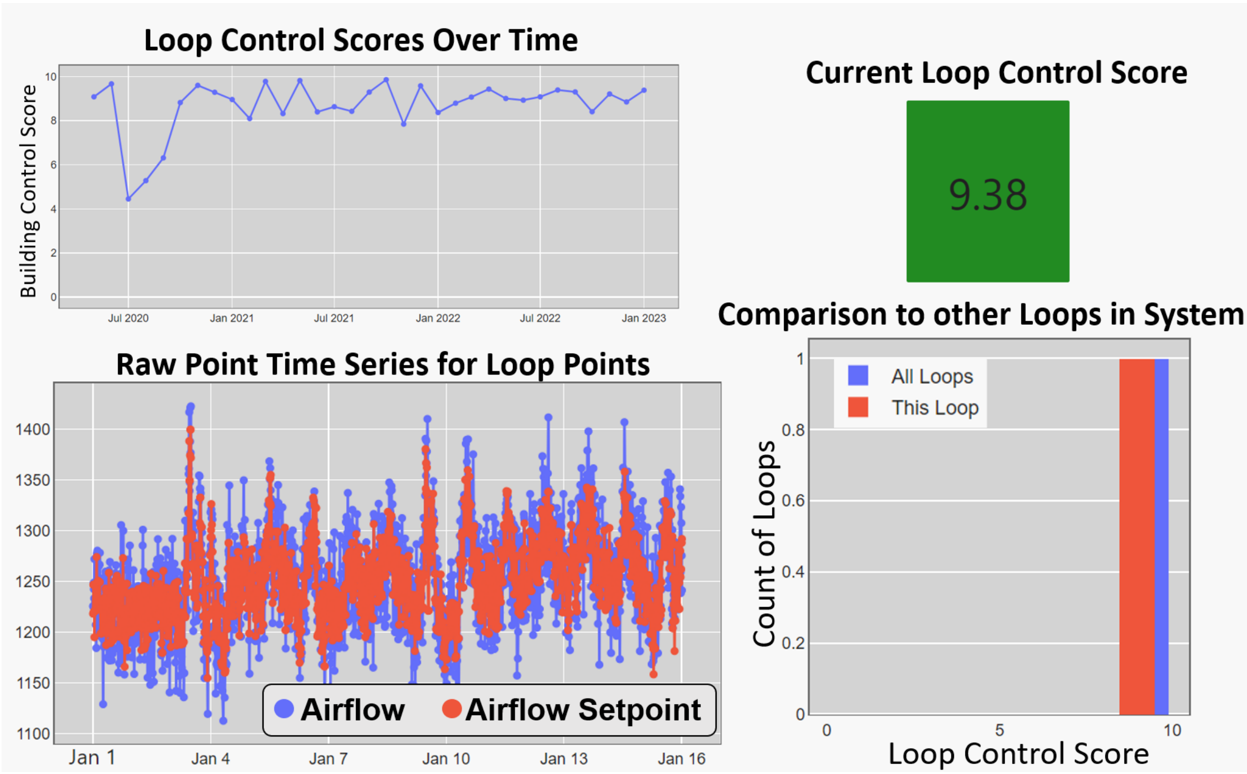

Figure 8. System 138 Supply Flow Loop Performance over Time

Table 5 below shows the systems in Section A.1 with the lowest 10 scores and the loops that are included in each of those systems. Four systems have a minimum score of 0. The systems mostly include supply air flow loops, with one including an exhaust flow and one being a chilled water loop.

Table 5. Section A.1: 10 Lowest Scoring Systems Information

System ID	System Control Score	System Loops
10	0.0	CHWS Temp
135	0.0	Supply Flow
145	0.0	Supply Flow
154	0.0	Supply Flow
153	0.03	Supply Flow
150	0.15	Exh Flow, Supply Flow
155	0.41	Supply Flow
149	0.79	Supply Flow
151	0.85	Supply Flow
143	4.03	Supply Flow

CHWS = chilled water supply; Exh = exhaust; ID = identification

Figure 9 below shows the score over time and the raw data for the chilled water temperature loop in system 10 (the only loop in the lowest scoring system). The control score over time shows some wide fluctuations but a trend toward returning to 0. The bottom left figure shows the raw time series data with the temperature setpoint in red and the temperature process variable in blue. The available setpoint data shows that the PV water temperature does not converge, leading to a low score of 0.

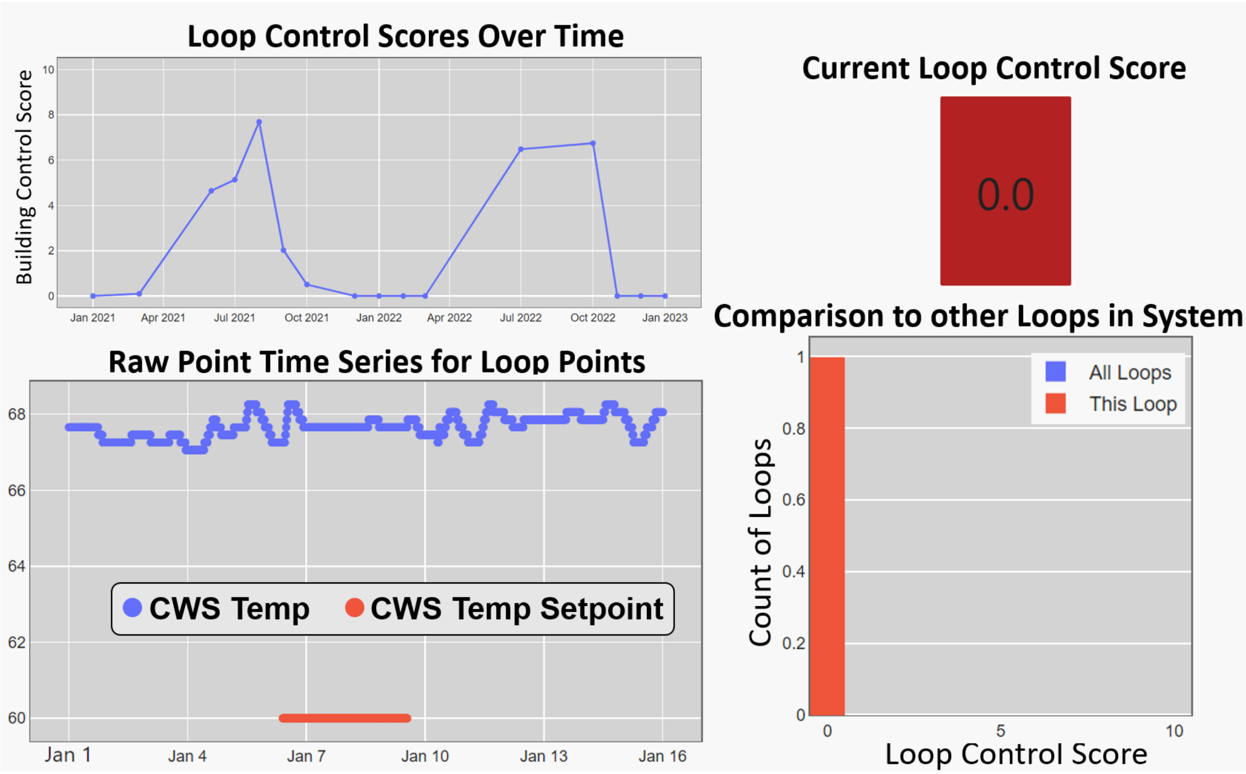

Figure 9. System 10 CHWS Loop Performance over Time

Figure 10 below shows the score over time and the raw data for the supply flow loop in System 10 (the only loop in the second lowest scoring system). The control score over time shows some small fluctuations but a strong trend toward 0. The bottom left figure shows the raw time series data with the flow setpoint in red and the flow process variable in blue. The time series shows that the supply flow does not change to approach the setpoint, leading to a low score of 0.

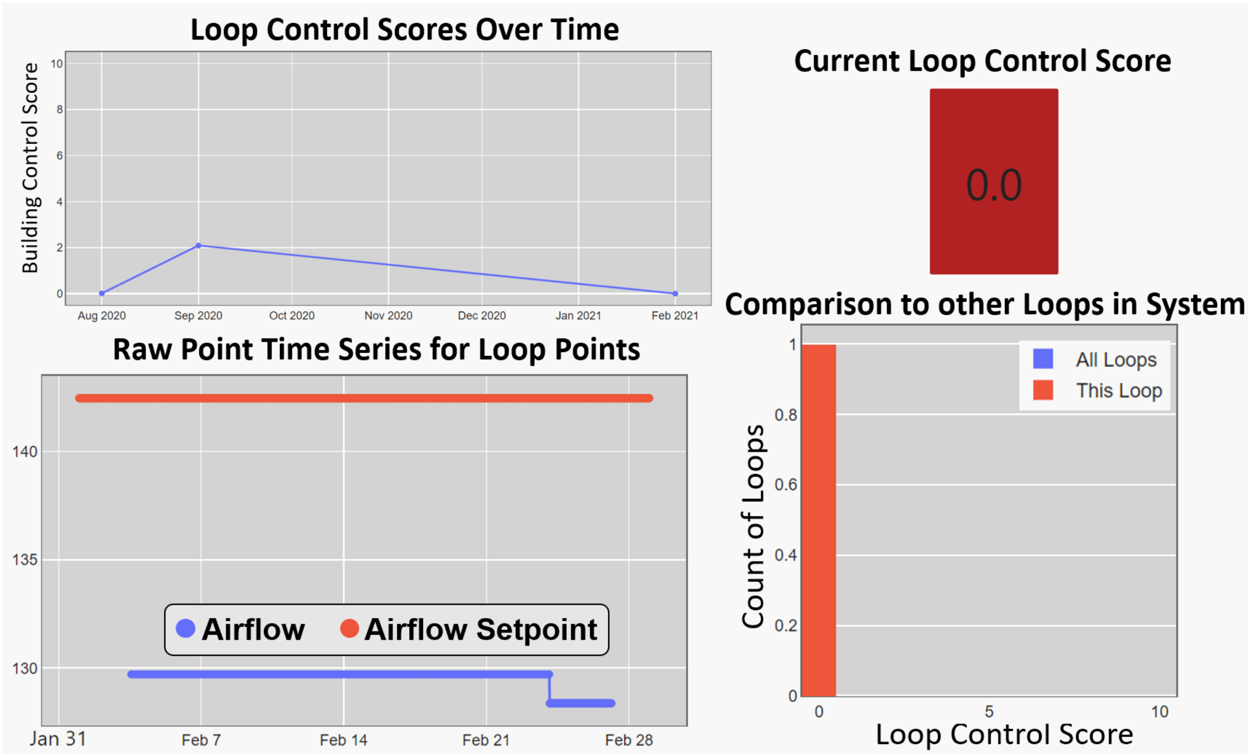

Figure 10. System 135 Supply Flow Loop Performance Over Time

2.4 Building Section A.2

Section A.2 scored a 6.14 overall. The trend of this score over time is shown in Figure 11 below. The behavior has remained relatively stable over time, with the score rarely falling below 5 or rising above 7.5.

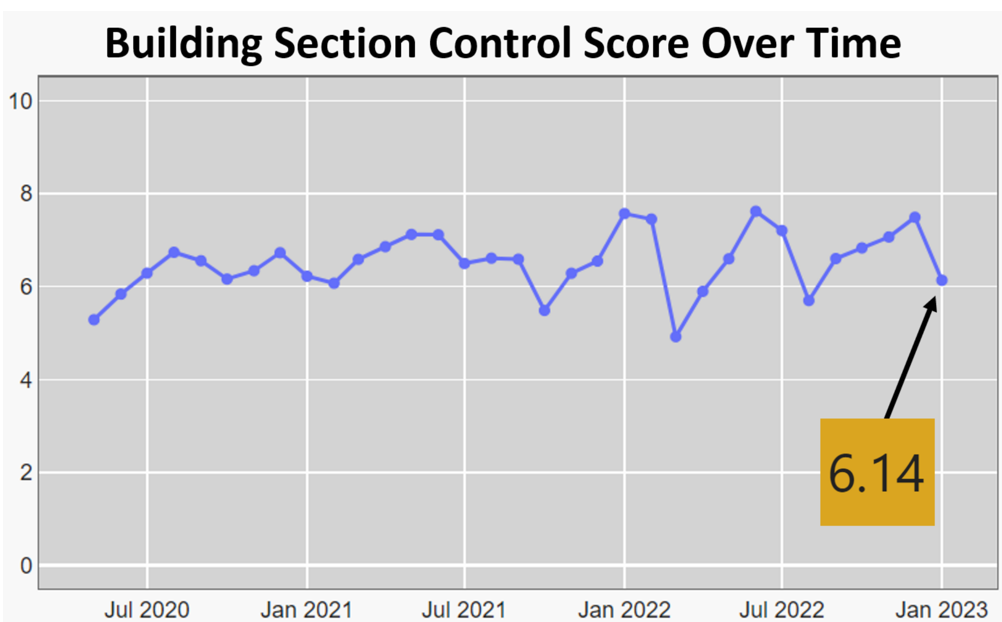

Figure 11. Section A.2 Control Scores Over Time

Section A.2 includes 23 different systems. The distribution of scores for these systems is shown in Figure 12 below. As can be seen, there are 11 systems with high performance (>7.5) and three systems with low performance (<1.5).

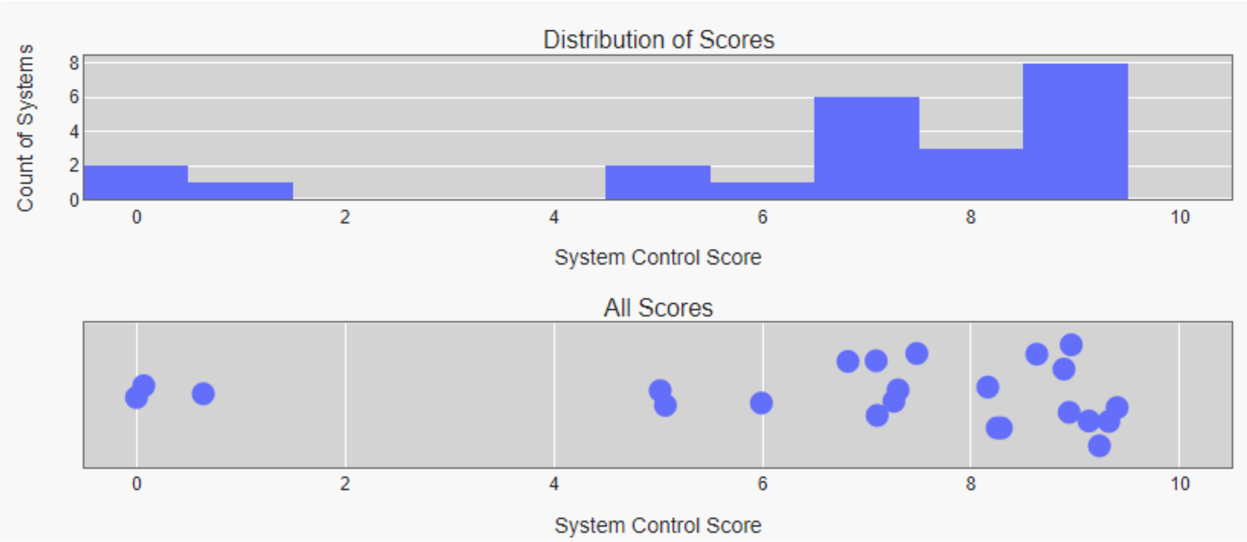

Figure 12. Distribution of System Scores within Section A.2

Table 6 below shows the systems in Section A.2 with the highest 10 scores and the loops that are included in each of those systems. The maximum system score achieved is 9.4. The systems mostly include supply air flow loops, exhaust flow loops or both, with one system having zone temperature and discharge air temperature loops.

Table 6. Section A.2: 10 Highest Scoring Systems Information

System ID	System Control Score	System Loops
258	9.4	Exh Flow, Supply Flow
257	9.32	Exh Flow, Supply Flow
260	9.23	Supply Flow
16	9.13	Zone Temp, Disch Air Temp
266	8.96	Exh Flow, Supply Flow
270	8.94	Exh Flow, Supply Flow
250	8.89	Exh Flow, Supply Flow
276	8.63	Exh Flow
249	8.29	Exh Flow, Supply Flow
267	8.25	Exh Flow, Supply Flow

Exh = exhaust; ID = identification

Figure 13 below shows the score over time and the raw data for the Exh Flow loop in system 266. The control score over time shows a steady trend around nine, with a few drops in performance. The bottom left figure shows the raw time series data with the exh flow setpoint in red and the exh air flow process variable in blue. The air flow seems to track the setpoint well through the changing values, resulting in a high 8.96 loop control score.

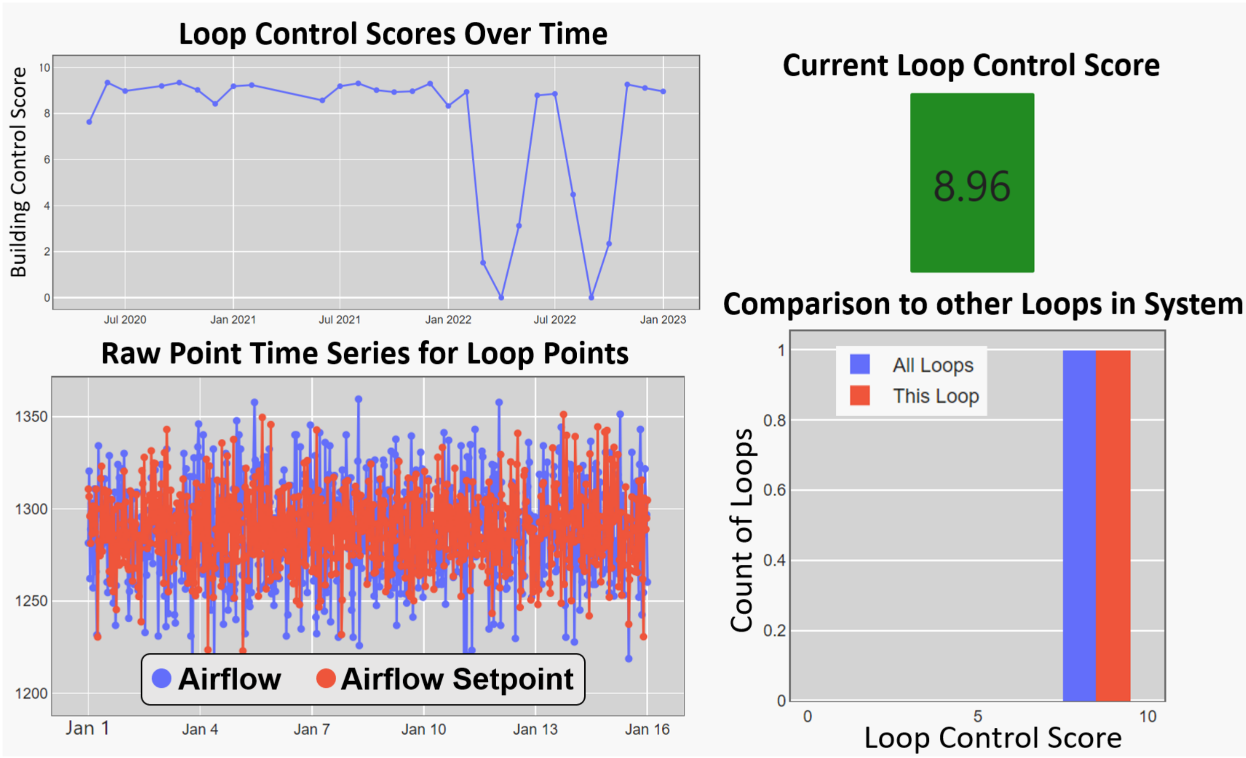

Figure 13. System 266 Exh Flow Loop Performance Over Time

Table 7 below shows the systems in Section A.2 with the lowest 10 scores and the loops that are included in each of those systems. Only one system has a minimum score of 0. The systems mostly include supply air flow loops, with some including exhaust flows and some including discharge air temperature.

Table 7. Section A.2: 10 Lowest Scoring Systems Information

System ID	System Control Score	System Loops
17	0.0	Zone Temp, Disch Air Temp
261	0.07	Supply Flow
263	0.64	Exh Flow, Supply Flow
262	5.02	Supply Flow
264	5.07	Exh Flow, Supply Flow
3	5.99	Supply Flow
259	6.82	Supply Flow
15	7.09	Disch Air Temp
269	7.1	Supply Flow
265	7.26	Exh Flow, Supply Flow

Disch = discharge; Exh = exhaust; ID = identification

Figure 14 below shows the score over time and the raw data for the zone air temperature loop in System 17. The control score over time shows a few short spikes but a trend toward returning to 0. The bottom left figure shows the raw time series data with the temperature setpoint in red and the temperature process variable in blue. The data shows that the zone temperature is offset from the setpoint, leading to a bad proximity and a low score of 0.

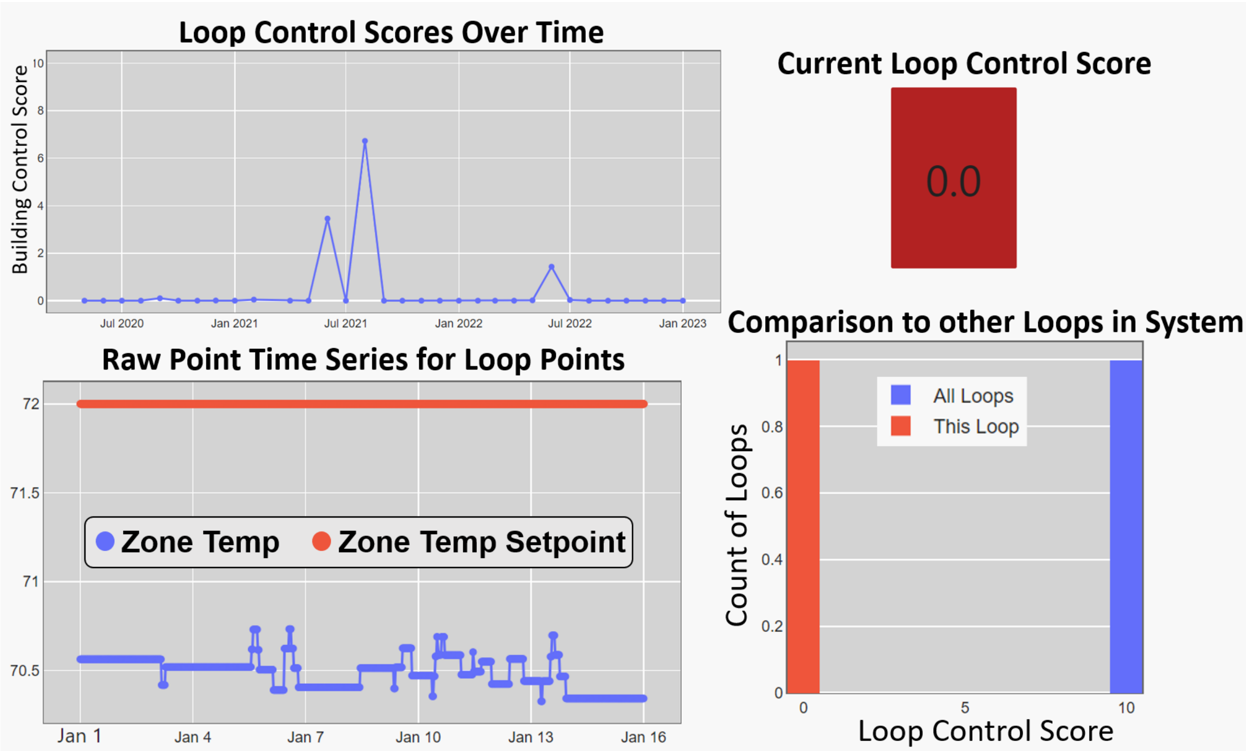

Figure 14. System 17 Zone Temp Loop Performance Over Time

2.5 Building Section A.3

Section A.3 scored a 4.55 overall. The trend of this score over time is shown in Figure 15 below. The behavior has remained relatively stable over time, with the score remaining mostly between 4 and 6.

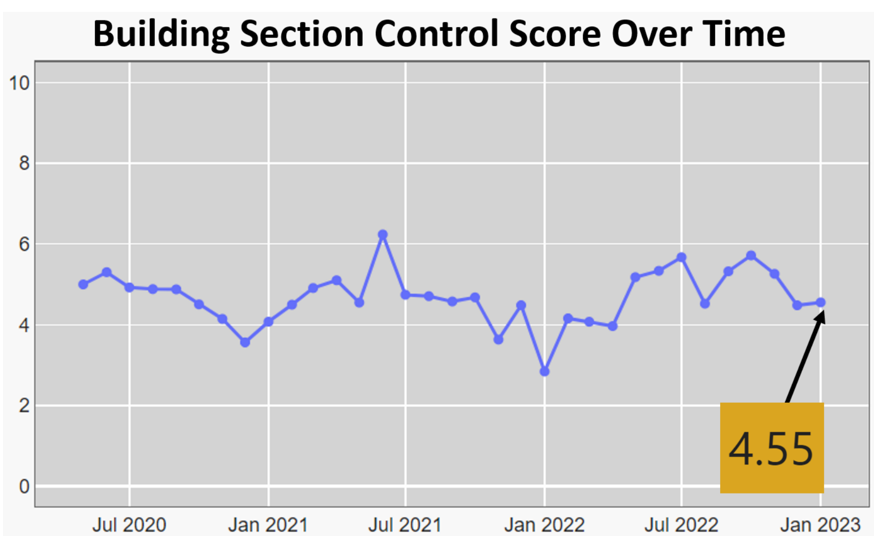

Figure 15. Section A.3 Control Scores Over Time

Section A.3 includes 47 different systems. The distribution of scores for these systems is shown in Figure 16 below. As can be seen, the systems are distributed relatively evenly with a cluster of 16 buildings between 5.5 and 7.5.

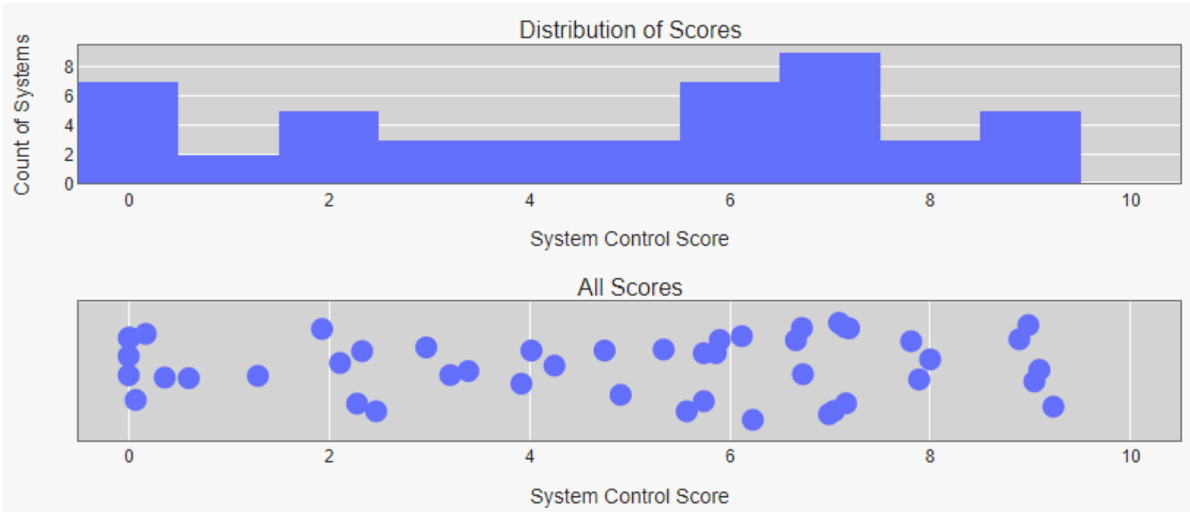

Figure 16. Distribution of System Scores within Section A.3

Table 8 below shows the systems in Section A.3 with the highest 10 scores and the loops that are included in each of those systems. The maximum system score achieved is 9.23. The systems all include supply air flow loops, with one including an exhaust flow loop.

Table 8. Section A.3: 10 Highest Scoring Systems Information

System ID	System Control Score	System Loops
58	9.23	Supply Flow
74	9.09	Supply Flow
60	9.04	Supply Flow
46	8.98	Exh Flow, Supply Flow
59	8.89	Supply Flow
44	8.0	Supply Flow
78	7.89	Supply Flow
61	7.81	Supply Flow
65	7.19	Supply Flow
56	7.16	Supply Flow

Exh = exhaust; ID = identification

Figure 17 below shows the score over time and the raw data for the supply flow loop in System 74. The control score over time shows some small variations but remains within a range of 6 to 9. The bottom left figure shows the raw time series data with the supply flow setpoint in red and the supply air flow process variable in blue. The air flow seems to track the setpoint well and follows the changes in setpoint, resulting in a high 9.09 loop control score.

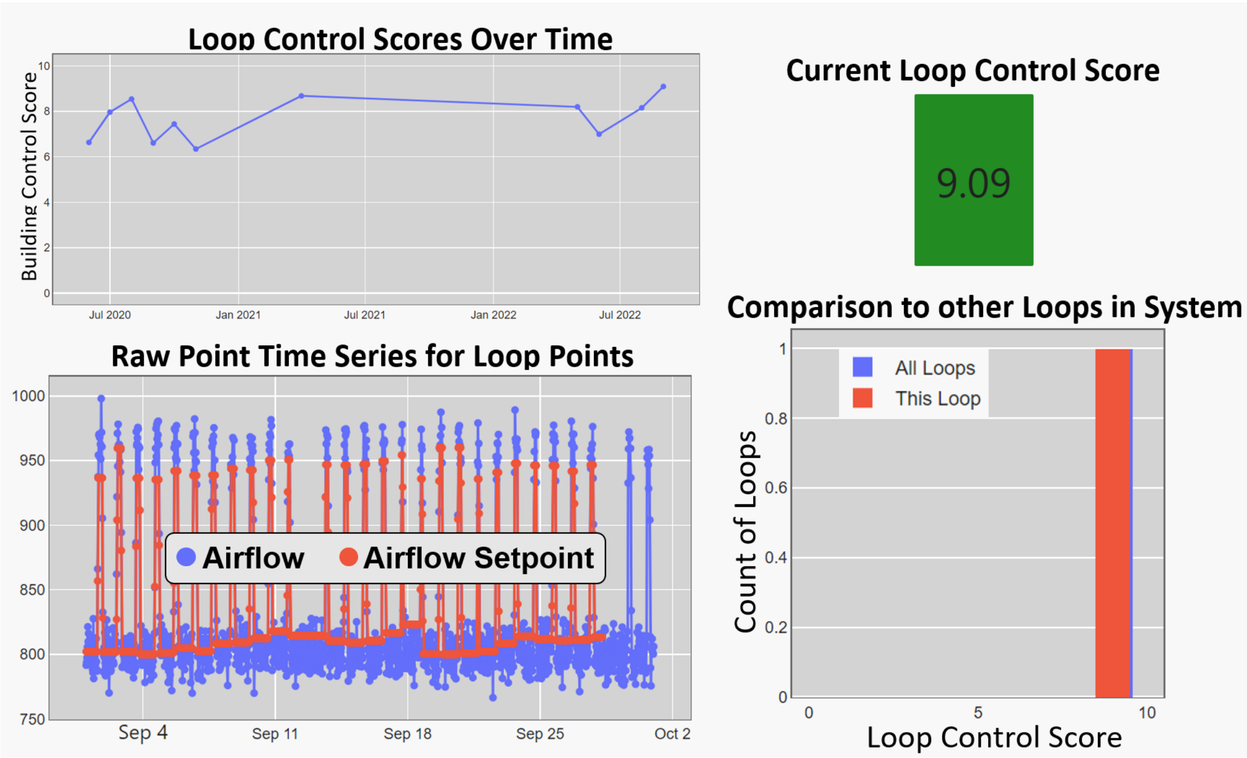

Figure 17. System 74 Supply Flow Loop Performance Over Time

Table 9 below shows the systems in Section A.3 with the lowest 10 scores and the loops that are included in each of those systems. Three systems have a minimum score of 0. The systems all include supply air flow loops, with one including an exhaust flow loop.

Table 9. Section A.3: 10 Lowest Scoring Systems Information

System ID	System Control Score	System Loops
45	0.0	Exh Flow, Supply Flow
77	0.0	Supply Flow
84	0.0	Supply Flow
66	0.01	Supply Flow
75	0.07	Supply Flow
85	0.17	Supply Flow
89	0.36	Supply Flow
91	0.6	Supply Flow
53	1.29	Supply Flow
48	1.93	Supply Flow

Exh = exhaust; ID = identification

Figure 18 below shows the score over time and the raw data for the exh flow loop in System 10. The control score over time is constant, near 0. The bottom left figure shows the raw time series data with the air flow setpoint in red and the air flow process variable in blue. The available setpoint data shows that the air flow is offset from the setpoint, leading to a low score of 0.

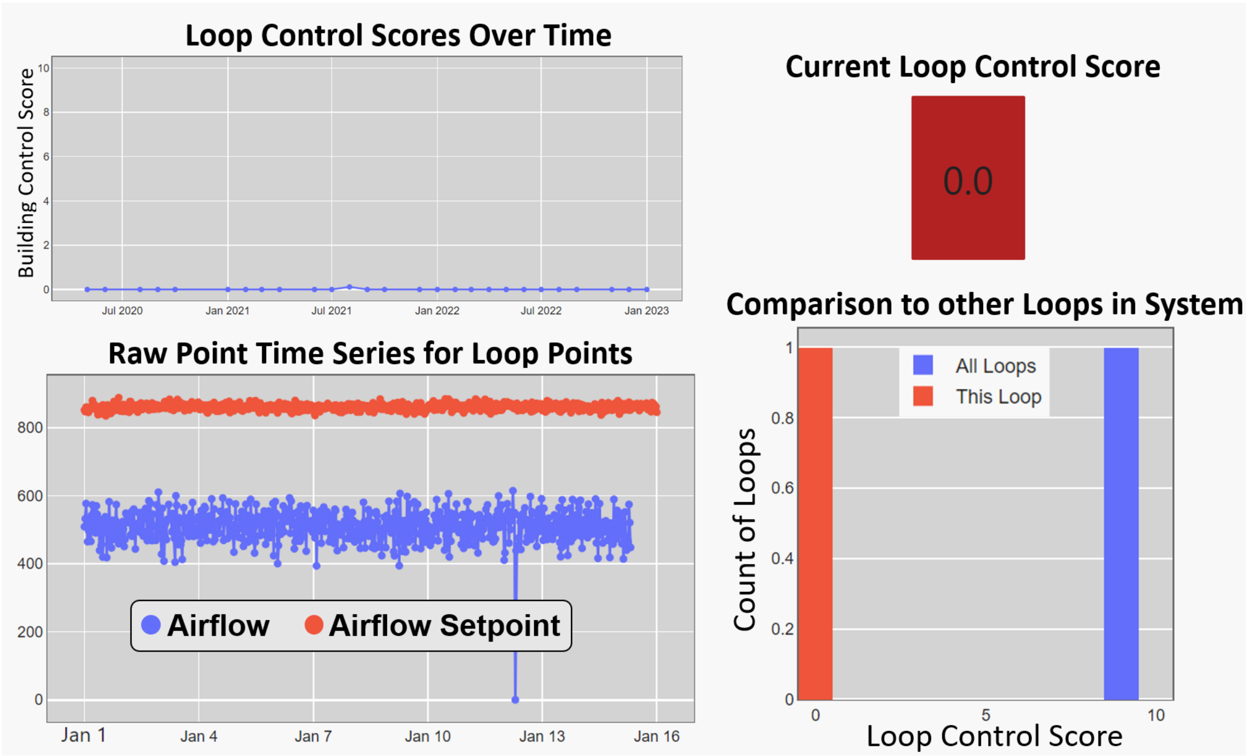

Figure 18. System 45 Exh Flow Loop Performance Over Time

2.6 Building Section A.4

Section A.4 scored 5.09 overall. The trend of this score over time is shown in Figure 19 below. The behavior has remained relatively stable over time, with the score remaining mostly between 4 and 6.

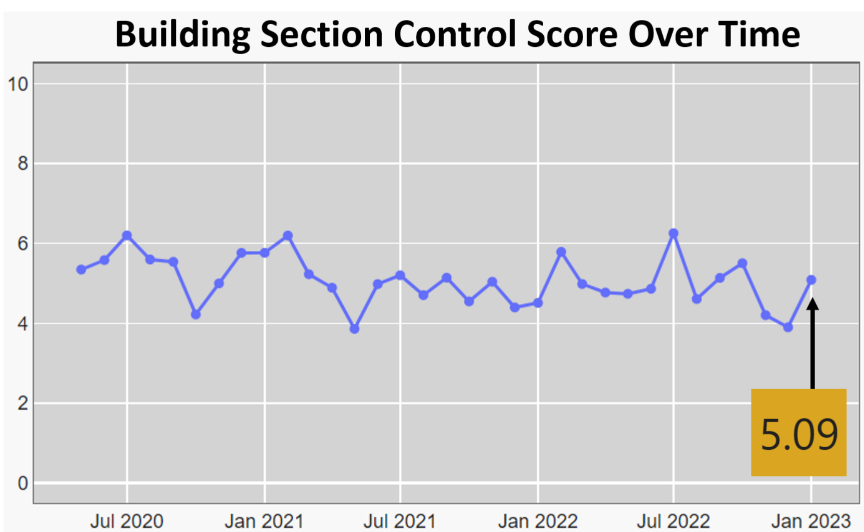

Figure 19. Section A.4 Control Scores Over Time

Section A.4 includes 18 different systems. The distribution of scores for these systems is shown in Figure 20 below. As can be seen, the system scores are clustered in three ranges, with six systems scoring lower than 1.5, three systems scoring between 4.5 and 5.5, and nine systems scoring between 6.5 and 9.5.

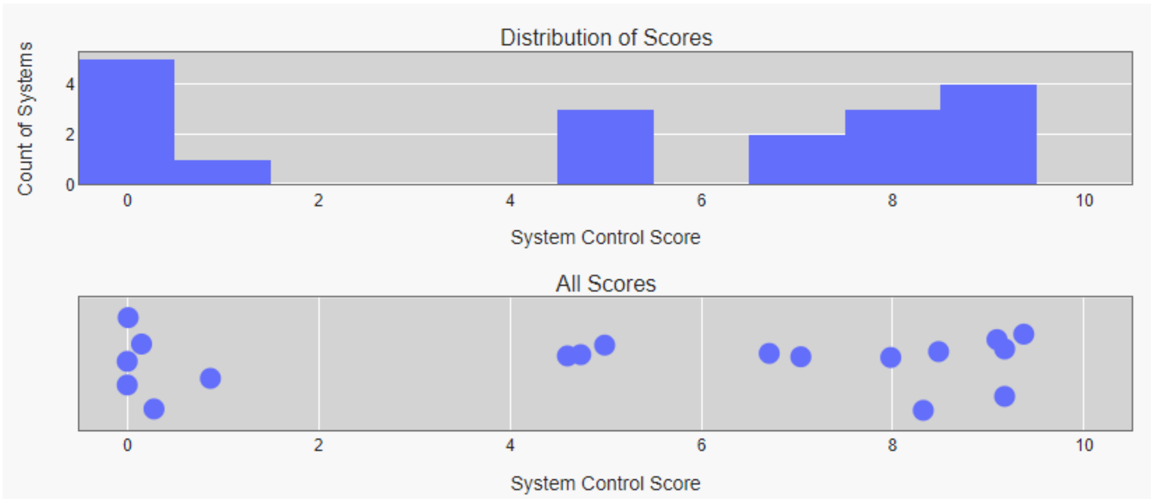

Figure 20. Distribution of System Scores within Section A.4

Table 10 below shows the systems in Section A.4 with the highest 10 scores and the loops that are included in each of those systems. The maximum system score achieved is 9.37. The systems all include supply air flow loops, with most including an exhaust flow loop and various other loops.

Table 10. Section A.4: 10 Highest Scoring Systems Information

System ID	System Control Score	System Loops
4	9.37	Exh Flow, Supply Flow, Zone Temp
192	9.17	Exh Flow, Supply Flow
195	9.17	Exh Flow, Supply Flow
193	9.09	Exh Flow, Supply Flow
194	8.48	Exh Flow, Supply Flow
191	8.32	Exh Flow, Supply Flow
196	7.98	Exh Flow, Supply Flow
181	7.04	Supply Flow
204	6.71	Disch Air Temp, Zone Temp, Exh Flow, Supply Flow
5	4.99	Disch Air Temp, Zone Humidity, Exh Flow, Supply Flow

Disch = discharge; Exh = exhaust; ID = identification

Figure 21 below shows the score over time and the raw data for the supply flow loop in System 4. The control score over time fluctuates a small amount but mostly stays near 10. The bottom left figure shows the raw time series data with the supply flow setpoint in red and the supply air flow process variable in blue. The air flow seems to track the changes in setpoint closely with the available data, resulting in a high 9.37 loop control score.

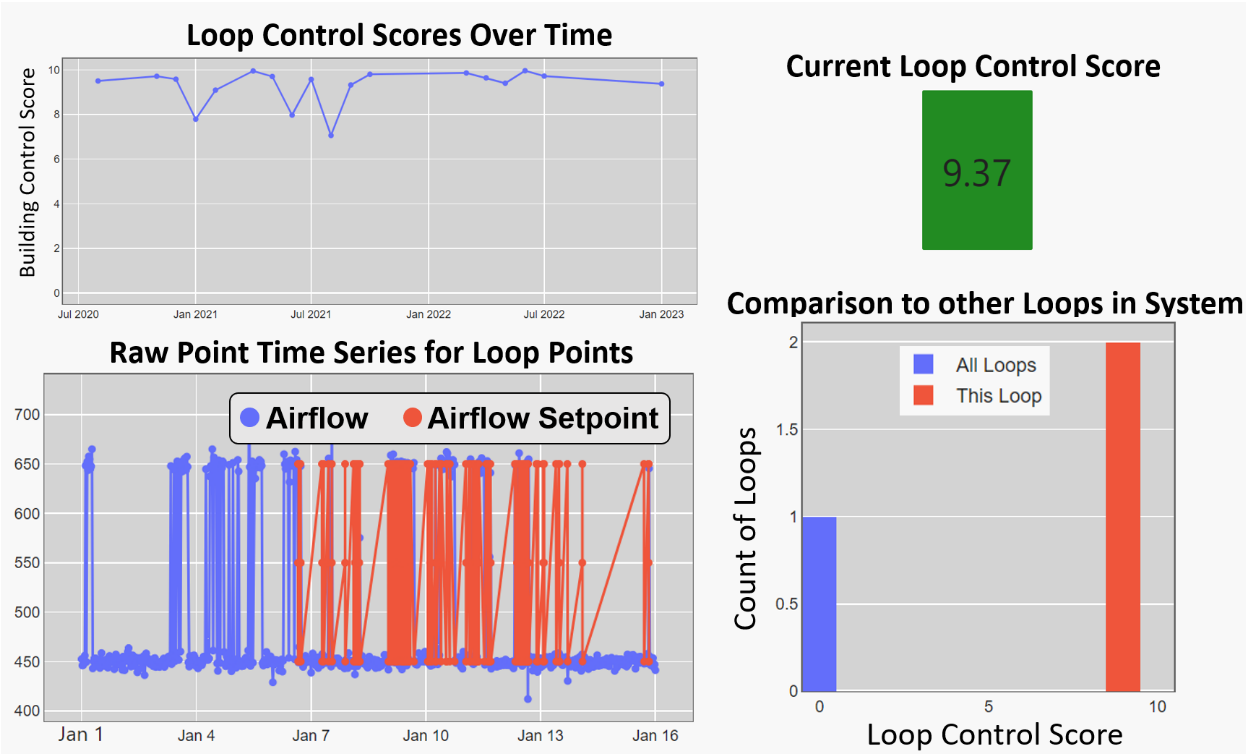

Figure 21. System 4 Supply Flow Loop Performance Over Time

Table 11 below shows the systems in Section A.4 with the lowest 10 scores and the loops that are included in each of those systems. Two systems have a minimum score of 0. The systems all include supply air flow loops, with some including an exhaust flow loop and various other loops.

Table 11. Section A.4: 10 Lowest Scoring Systems Information

System ID	System Control Score	System Loops
184	0.0	Exh Flow, Supply Flow
185	0.0	Exh Flow, Supply Flow, Zone Temp
180	0.01	Supply Flow
21	0.15	Disch Air Temp, Zone Temp, Exh Flow, Supply Flow
182	0.28	Exh Flow, Supply Flow
183	0.87	Exh Flow, Supply Flow
206	4.6	Disch Air Temp, Zone Temp, Exh Flow, Supply Flow
202	4.74	Disch Air Temp, Zone Temp, Exh Flow, Supply Flow
5	4.99	Disch Air Temp, Zone Humidity, Exh Flow, Supply Flow
204	6.71	Disch Air Temp, Zone Temp, Exh Flow, Supply Flow

Disch = discharge; Exh = exhaust; ID = identification

Figure 22 below shows the score over time and the raw data for the exh flow loop in System 184. The control score over time shows a few short-term fluctuations but a trend toward returning to 0. The bottom left figure shows the raw time series data, with the slow setpoint in red and the flow process variable in blue. The available setpoint data shows that the PV flow is not stable and is offset from the setpoint, leading to a low score of 0.

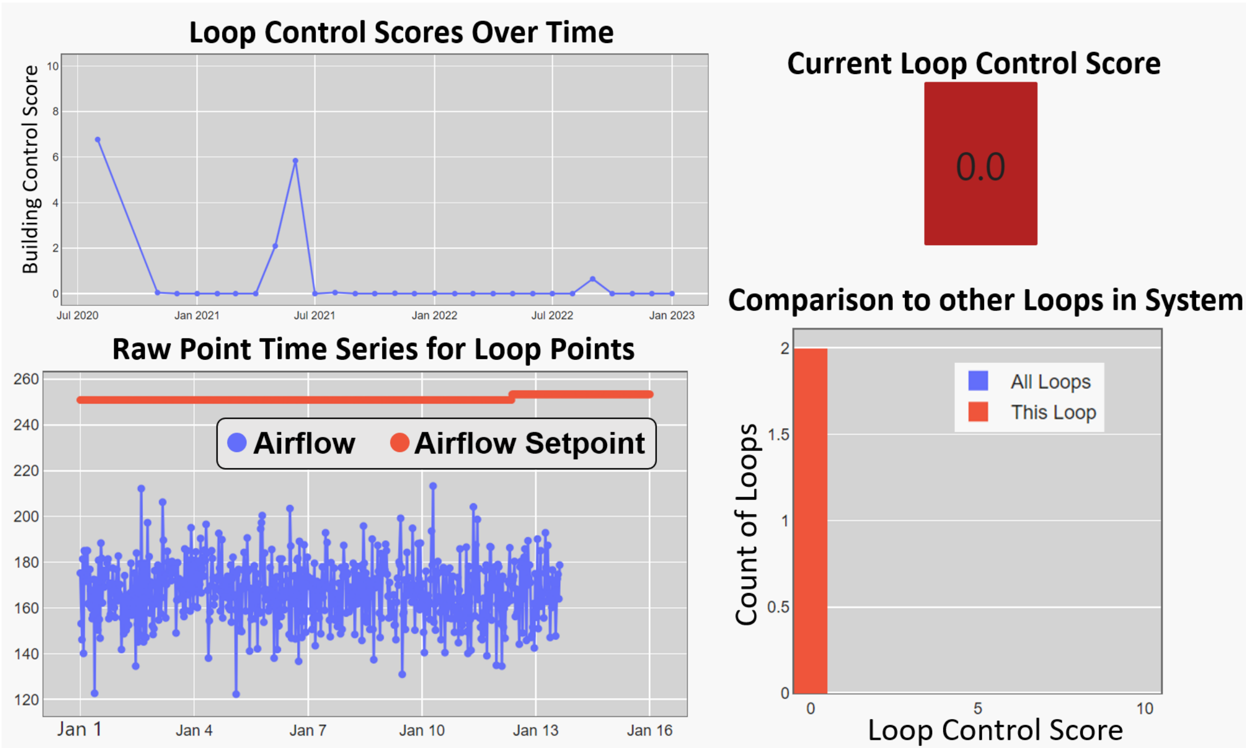

Figure 22. System 184 Exh Flow Loop Performance Over Time

3.0 Conclusion

The Building ControlScore application analyzed historical control system data captured over a two-and-a-half-year period from a laboratory building. The investigation revealed that, overall, the building exhibited good control performance. However, the analysis also identified clusters of poorly performing systems within the building, which could be improved.

Section 3.1 provides recommendations for which systems should be prioritized for further investigation. The systems highlighted were consistently unable to reach the setpoints provided by the control systems. Investigating these issues could uncover opportunities for energy savings or improved system performance. In the case of laboratory ventilation rates, identifying which systems are unable to meet their airflow setpoints could also improve occupant safety.

All the building sections had a small cluster of systems that exhibited poor control performance. Finding similarities between these systems could help understand other systems in buildings that are not yet incorporated into ControlScore or systems in the building that could not be added to the tool due to metadata availability.

The work documented in this report has also highlighted potential areas of enhancement for the ControlScore tool. The proposed expansion of the tool's capabilities would increase its reach by reducing the time required for integration and providing the latest analysis of the buildings' control performance.

3.1 Laboratory Building A Systems Identified by ControlScore as Needing Investigation

The ControlScore provides performance feedback that allows building operators to identify areas of poor performance that can be investigated and addressed. Table 12 below shows the system in all sections of the building with scores less than 1. For systems with multiple loops, the loops with poor performance are bolded. These systems received the lowest scores in the building and should be the highest priority for further investigation.

Some common issues with the PV include consistent positive error (where PV is higher than SP), consistent negative error (where PV is lower than SP), and unstable behavior (where PV oscillates a lot). Flow loops suffering from positive error have higher flowrates than the setpoint. Resolving this issue could lead to energy savings from reduced fan operation. Temperature loops suffering from positive error have higher temperatures than the setpoint. These issues could result from excess heating or insufficient cooling capacity. Flow loops with negative error issues have a flowrate lower than the setpoint. These systems are not able to supply or exhaust the intended amount of air with the current equipment. Temperature loops with a negative error have too low a temperature and could arise from excess cooling or insufficient heating. Investigating these poorly performing loops is recommended and should be grouped according to the issues that are present, since loops with similar issues may have similar solutions.

Table 12. Building Systems with a Score <1

System ID	Building Section	System Control Score	System Loops	Issue with PV
10	A.1	0.0	CHWS Temp	Positive Error

System ID	Building Section	System Control Score	System Loops	Issue with PV
135	A.1	0.0	Supply Flow	Positive Error
145	A.1	0.0	Supply Flow	Positive Error
154	A.1	0.0	Supply Flow	Negative Error
153	A.1	0.03	Supply Flow	Negative Error
150	A.1	0.15	**Exh Flow**, Supply Flow	Negative Error
155	A.1	0.41	Supply Flow	Negative Error
149	A.1	0.79	Supply Flow	Positive Error
151	A.1	0.85	Supply Flow	Negative Error
17	A.2	0.0	**Zone Temp**, Disch Air Temp	Negative Error
261	A.2	0.07	Supply Flow	Negative Error
263	A.2	0.64	Exh Flow, **Supply Flow**	Negative Error, Unstable
45	A.3	0.0	**Exh Flow**, Supply Flow	Negative Error
77	A.3	0.0	Supply Flow	Negative Error
84	A.3	0.0	Supply Flow	Positive Error
66	A.3	0.01	Supply Flow	Negative Error
75	A.3	0.07	Supply Flow	Negative Error
85	A.3	0.17	Supply Flow	Negative Error, Unstable
89	A.3	0.36	Supply Flow	Positive Error
91	A.3	0.6	Supply Flow	Negative Error
184	A.4	0.0	**Exh Flow, Supply Flow**	Negative Error, Unstable, Positive Error
185	A.4	0.0	Exh Flow, Supply Flow, **Zone Temp**	Negative Error
180	A.4	0.01	Supply Flow	Negative Error
21	A.4	0.15	Disch Air Temp, **Zone Temp, Exh Flow**, Supply Flow	Positive Error
182	A.4	0.28	**Exh Flow**, Supply Flow	Positive Error
183	A.4	0.87	**Exh Flow**, Supply Flow	Positive Error

CHWS = chilled water supply; Disch = discharge; Exh = exhaust; ID = identification; PV = process variable

3.2 Potential ControlScore Tool Enhancements

Most of the work to deploy the tool at the new building was extracting the required metadata for the tool, as described in Section 2.1. Because the effort primarily relied on the point naming convention implemented in the historian database, it was limited and error prone. Formal metadata models, often referred to as semantic models, fully describe what each control point represents and how the points relate to each other. There are several emerging standards for these semantic models (e.g., Project Haystack, Brick Schema, and ASHRAE Standard 223P), but they have not been widely adopted throughout the building industry. ControlScore serves as one valuable example of a use case that these semantic models enable. Future work could investigate incorporating one or more of these semantic models into ControlScore and replace the manual metadata extraction with a fully automated process. Automated metadata generation would improve the scalability of the tool by several orders of magnitude.

PNNL is actively integrating a portion of the campus with SkySpark, a leading energy management information system. At the same time, SkySpark is actively investigating incorporating the ControlScore methodology into their environment through a trial license of the tool. Because SkySpark integration requires Haystack semantic model creation for each building, buildings already incorporated into SkySpark could have access to their ControlScore with very little setup required. Additional funding could be used to improve the ControlScore tool's incorporation into the SkySpark environment. With full integration into SkySpark, ControlScore could be deployed widely at buildings at PNNL and throughout the world.

The Facilities and Operations team provided valuable feedback on refinements that would make the tool more accessible and intuitive for users, particularly those who are not already familiar with the tool. These improvements include more explanatory material (similar to an "About" page) and documentation on how to use the tool and what the scores represent.

Finally, this deployment ControlScore at PNNL is based on a static copy of the historical database of a single building. The process of exporting the static copy was done manually and would need to be completely repeated to update the scores with data from the time since the copy of the database was originally made. Such manual efforts are time consuming, error prone, and not considered best practice for similar analytic tools. Provisioning the required cloud infrastructure for an automated data pipeline that would regularly pull in updated data for the tool so that it could provide up-to-date insights on the building's ControlScore would be valuable.

4.0 References

Salsbury, T. I., A. P. Rogers, T. A. Yoder, S. R. Johnson, and X. Duan. 2023. “A New Control Score Concept for Building Performance Assessment.” *Journal of Building Engineering* 66 (2023): 105770. https://doi.org/10.1016/j.jobe.2022.105770.

Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354

1-888-375-PNNL (7665)

www.pnnl.gov