Supplementary Information

A Sim-to-Real Transfer Learning-Based Convolutional Variational Autoencoder for Smart Manufacturing with Limited and Heterogeneous Data: A Thermoforming Case Study

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Table A.1 summarized the factory raw data collected and used for the thermoforming case study presented in the paper. The table includes the tabular features, i.e., sheet's maximum temperature, heating element's maximum temperature, vacuum pressure duration, Cooling fan delay time, and raw thermoplastic sheet batch number, along with the image numbers corresponding to the sheets’ thermal distribution images. Finally, the last two columns represent the thickness measurements at two critical locations, namely, the corner and bottom of the manufactured parts. They were employed as the outputs of the regression model in the proposed framework. Please note that only the labelled instances (i.e., experiments with thickness measurements) are included in the table. As elaborated in the manuscript, the unlabeled thermal images were also used as part of the data in the training of the ConvVAE (section 3.2). The raw data of this case study (including the Excel file and thermal images) are provided along with the manuscript for the interested readers.

Table A.1. Raw data used for the industrial thermoforming case study.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Trial number** | **Raw thermoplastic sheet batch number** | **Cooling fan delay time (s)** | **Sheet's maximum temperature (°C)** | **Heating element's maximum temperature (°C)** | **Vacuum pressure duration (s)** | **Mould category** | **Date** | **Image number** | **Thickness - bottom** | **Thickness - corner** |
| 1 | 1 | 20 | 171 | 365 | 95 | 8 | 2019-07-16 | T01 | 1.04 | 0.81 |
| 2 | 2 | 25 | 166 | 335 | 100 | 1 | 2019-07-16 | T02 | 1.07 | 0.86 |
| 3 | 1 | 20 | 170 | 365 | 95 | 8 | 2019-07-16 | T03 | 0.8 | 0.99 |
| 4 | 2 | 25 | 166 | 335 | 100 | 1 | 2019-07-16 | T04 | 1.04 | 0.83 |
| 5 | 2 | 25 | 173 | 335 | 100 | 1 | 2019-07-16 | T05 | 1.13 | 0.79 |
| 6 | 2 | 25 | 178 | 335 | 100 | 1 | 2019-07-16 | T06 | 0.94 | 0.72 |
| 7 | 2 | 25 | 169 | 335 | 100 | 1 | 2019-07-16 | T07 | 1.08 | 0.79 |
| 8 | 1 | 20 | 166 | 360 | 85 | 6 | 2019-07-16 | T08 | 0.94 | 0.79 |
| 9 | 1 | 20 | 167 | 360 | 85 | 6 | 2019-07-16 | T09 | 0.9 | 0.82 |
| 10 | 1 | 20 | 170 | 360 | 85 | 6 | 2019-07-16 | T10 | 0.87 | 0.81 |
| 11 | 1 | 20 | 167 | 360 | 85 | 6 | 2019-07-16 | T11 | 0.9 | 0.74 |
| 12 | 1 | 20 | 169 | 360 | 85 | 6 | 2019-07-16 | T12 | 0.89 | 0.74 |
| 13 | 1 | 20 | 172 | 360 | 85 | 6 | 2019-07-16 | T13 | 0.83 | 0.77 |
| 14 | 1 | 20 | 165 | 360 | 85 | 6 | 2019-07-16 | T14 | 0.81 | 0.77 |
| 15 | 2 | 20 | 166 | 335 | 125 | 7 | 2019-07-16 | T15 | 0.8 | 0.64 |
| 16 | 1 | 20 | 169 | 360 | 85 | 6 | 2019-07-16 | T17 | 1.12 | 0.73 |
| 17 | 2 | 20 | 180 | 335 | 125 | 7 | 2019-07-16 | T18 | 0.75 | 0.68 |
| 18 | 2 | 25 | 164 | 340 | 100 | 2 | 2019-07-17 | T03 | 0.92 | 0.99 |
| 19 | 3 | 22 | 162 | 330 | 115 | 3 | 2019-07-17 | T04 | 1.02 | 0.91 |
| 20 | 2 | 25 | 165 | 340 | 100 | 2 | 2019-07-17 | T05 | 0.92 | 1.05 |
| 21 | 3 | 22 | 159 | 330 | 115 | 3 | 2019-07-17 | T06 | 1.01 | 0.86 |
| 22 | 2 | 25 | 164 | 340 | 100 | 2 | 2019-07-17 | T07 | 0.88 | 1.04 |
| 23 | 3 | 22 | 166 | 330 | 115 | 3 | 2019-07-17 | T08 | 0.95 | 0.97 |
| 24 | 3 | 22 | 165 | 330 | 115 | 3 | 2019-07-17 | T10 | 0.92 | 0.95 |
| 25 | 2 | 25 | 161 | 340 | 100 | 5 | 2019-07-17 | T11 | 0.95 | 0.84 |
| 26 | 3 | 22 | 165 | 330 | 115 | 3 | 2019-07-17 | T12 | 1.1 | 0.84 |
| 27 | 2 | 25 | 166 | 340 | 100 | 5 | 2019-07-17 | T13 | 0.81 | 0.96 |
| 28 | 3 | 22 | 165 | 330 | 115 | 3 | 2019-07-17 | T14 | 0.93 | 0.78 |
| 29 | 2 | 25 | 162 | 340 | 100 | 5 | 2019-07-17 | T15 | 0.84 | 1.03 |
| 30 | 3 | 22 | 166 | 330 | 115 | 3 | 2019-07-17 | T16 | 0.93 | 0.86 |
| 31 | 2 | 25 | 163 | 340 | 100 | 5 | 2019-07-17 | T17 | 0.92 | 0.97 |
| 32 | 3 | 22 | 167 | 330 | 115 | 3 | 2019-07-17 | T18 | 0.95 | 0.82 |
| 33 | 2 | 25 | 163 | 340 | 100 | 5 | 2019-07-17 | T19 | 0.92 | 1.05 |
| 34 | 3 | 22 | 164 | 330 | 115 | 1 | 2019-07-17 | T20 | 0.94 | 0.85 |
| 35 | 2 | 25 | 163 | 340 | 100 | 5 | 2019-07-17 | T21 | 0.9 | 1.03 |
| 36 | 3 | 22 | 172 | 330 | 115 | 1 | 2019-07-17 | T22 | 1.03 | 0.76 |
| 37 | 2 | 25 | 168 | 340 | 100 | 5 | 2019-07-17 | T23 | 0.94 | 0.98 |
| 38 | 3 | 22 | 172 | 330 | 115 | 1 | 2019-07-17 | T24 | 0.98 | 0.86 |
| 39 | 2 | 25 | 165 | 340 | 100 | 5 | 2019-07-17 | T25 | 0.95 | 0.96 |
| 40 | 3 | 22 | 167 | 330 | 115 | 1 | 2019-07-17 | T26 | 0.94 | 0.84 |
| 41 | 2 | 25 | 165 | 340 | 100 | 5 | 2019-07-17 | T27 | 0.95 | 1 |
| 42 | 2 | 22 | 178 | 330 | 100 | 3 | 2019-07-19 | T01 | 0.92 | 0.86 |
| 43 | 2 | 20 | 169 | 365 | 90 | 8 | 2019-07-19 | T02 | 0.95 | 1.12 |
| 44 | 2 | 22 | 174 | 330 | 100 | 3 | 2019-07-19 | T03 | 0.88 | 0.92 |
| 45 | 2 | 22 | 177 | 330 | 100 | 3 | 2019-07-19 | T04 | 0.96 | 0.79 |
| 46 | 2 | 20 | 168 | 370 | 80 | 8 | 2019-07-19 | T05 | 0.95 | 1.03 |
| 47 | 2 | 22 | 169 | 330 | 100 | 3 | 2019-07-19 | T06 | 0.94 | 0.9 |
| 48 | 2 | 20 | 167 | 370 | 80 | 8 | 2019-07-19 | T07 | 0.98 | 1.04 |
| 49 | 2 | 22 | 168 | 330 | 100 | 3 | 2019-07-19 | T08 | 0.86 | 0.9 |
| 50 | 2 | 20 | 169 | 370 | 80 | 8 | 2019-07-19 | T09 | 0.97 | 1.16 |
| 51 | 2 | 22 | 167 | 330 | 100 | 3 | 2019-07-19 | T10 | 0.92 | 0.89 |
| 52 | 2 | 22 | 172 | 330 | 100 | 3 | 2019-07-19 | T11 | 0.93 | 0.9 |
| 53 | 2 | 22 | 175 | 330 | 100 | 3 | 2019-07-19 | T12 | 0.93 | 0.86 |
| 54 | 2 | 22 | 177 | 330 | 100 | 3 | 2019-07-19 | T13 | 0.91 | 0.82 |
| 55 | 2 | 25 | 168 | 340 | 100 | 2 | 2019-07-19 | T14 | 0.83 | 1.05 |
| 56 | 2 | 25 | 177 | 340 | 100 | 2 | 2019-07-19 | T15 | 0.9 | 0.86 |
| 57 | 2 | 22 | 169 | 330 | 100 | 3 | 2019-07-19 | T16 | 0.85 | 0.96 |
| 58 | 2 | 22 | 171 | 330 | 100 | 3 | 2019-07-19 | T17 | 0.86 | 0.77 |
| 59 | 2 | 25 | 167 | 340 | 100 | 2 | 2019-07-19 | T18 | 0.85 | 1.06 |
| 60 | 2 | 22 | 172 | 330 | 100 | 3 | 2019-07-19 | T19 | 0.85 | 0.85 |
| 61 | 2 | 25 | 168 | 340 | 100 | 2 | 2019-07-19 | T20 | 0.84 | 1.1 |
| 62 | 2 | 22 | 174 | 330 | 100 | 3 | 2019-07-19 | T21 | 0.86 | 0.8 |
| 63 | 2 | 25 | 170 | 340 | 100 | 2 | 2019-07-19 | T22 | 0.8 | 1 |
| 64 | 2 | 25 | 166 | 340 | 100 | 5 | 2019-07-22 | T02 | 0.84 | 1 |
| 65 | 2 | 22 | 177 | 330 | 100 | 3 | 2019-07-22 | T03 | 0.87 | 0.88 |
| 66 | 2 | 25 | 169 | 340 | 100 | 5 | 2019-07-22 | T04 | 0.8 | 1.01 |
| 67 | 2 | 22 | 172 | 330 | 100 | 3 | 2019-07-22 | T05 | 0.87 | 0.88 |
| 68 | 2 | 22 | 177 | 330 | 100 | 3 | 2019-07-22 | T06 | 0.9 | 0.87 |
| 69 | 2 | 22 | 178 | 330 | 100 | 3 | 2019-07-22 | T07 | 0.93 | 0.8 |
| 70 | 2 | 22 | 178 | 330 | 100 | 3 | 2019-07-22 | T08 | 0.9 | 0.77 |
| 71 | 2 | 20 | 174 | 335 | 125 | 7 | 2019-07-22 | T09 | 0.82 | 1.05 |
| 72 | 2 | 22 | 171 | 330 | 100 | 3 | 2019-07-22 | T10 | 0.89 | 0.81 |
| 73 | 2 | 20 | 172 | 335 | 125 | 7 | 2019-07-22 | T11 | 1.02 | 0.74 |
| 74 | 2 | 22 | 174 | 330 | 100 | 3 | 2019-07-22 | T12 | 0.86 | 0.9 |
| 75 | 2 | 20 | 171 | 335 | 125 | 7 | 2019-07-22 | T13 | 0.83 | 1.08 |
| 76 | 2 | 22 | 172 | 330 | 100 | 3 | 2019-07-22 | T14 | 0.81 | 1.1 |
| 77 | 2 | 20 | 171 | 335 | 125 | 7 | 2019-07-22 | T15 | 0.89 | 0.81 |
| 78 | 2 | 22 | 170 | 330 | 100 | 3 | 2019-07-22 | T16 | 0.88 | 0.76 |
| 79 | 2 | 22 | 170 | 330 | 100 | 3 | 2019-07-22 | T18 | 0.94 | 0.8 |
| 80 | 2 | 22 | 171 | 330 | 100 | 3 | 2019-07-22 | T21 | 0.77 | 1.12 |
| 81 | 2 | 20 | 173 | 335 | 125 | 7 | 2019-07-22 | T22 | 1.27 | 0.68 |
| 82 | 2 | 22 | 176 | 330 | 100 | 3 | 2019-07-22 | T24 | 1.33 | 0.63 |
| 83 | 2 | 20 | 172 | 360 | 110 | 6 | 2019-07-22 | T25 | 0.75 | 0.98 |
| 84 | 2 | 20 | 168 | 360 | 110 | 6 | 2019-07-22 | T27 | 0.78 | 0.94 |
| 85 | 2 | 25 | 170 | 340 | 100 | 2 | 2019-07-23 | T01 | 1.24 | 0.76 |
| 86 | 2 | 22 | 171 | 330 | 100 | 1 | 2019-07-23 | T02 | 1.19 | 0.66 |
| 87 | 2 | 25 | 165 | 340 | 100 | 2 | 2019-07-23 | T03 | 1.27 | 0.72 |
| 88 | 2 | 22 | 170 | 330 | 100 | 1 | 2019-07-23 | T04 | 1.18 | 0.73 |
| 89 | 2 | 25 | 164 | 340 | 100 | 2 | 2019-07-23 | T05 | 1.16 | 0.78 |
| 90 | 2 | 22 | 167 | 330 | 100 | 1 | 2019-07-23 | T06 | 1.11 | 0.78 |
| 91 | 2 | 25 | 162 | 340 | 100 | 2 | 2019-07-23 | T07 | 1.29 | 0.71 |
| 92 | 2 | 22 | 167 | 330 | 100 | 1 | 2019-07-23 | T08 | 1.14 | 0.73 |
| 93 | 2 | 25 | 162 | 340 | 100 | 2 | 2019-07-23 | T09 | 1.04 | 0.72 |
| 94 | 2 | 22 | 167 | 330 | 100 | 1 | 2019-07-23 | T10 | 1.16 | 0.71 |
| 95 | 2 | 25 | 160 | 340 | 100 | 2 | 2019-07-23 | T11 | 1 | 0.79 |
| 96 | 2 | 22 | 164 | 330 | 100 | 1 | 2019-07-23 | T12 | 1.2 | 0.7 |
| 97 | 2 | 25 | 158 | 340 | 100 | 2 | 2019-07-23 | T13 | 1.04 | 0.76 |
| 98 | 2 | 22 | 162 | 330 | 100 | 1 | 2019-07-23 | T14 | 1.13 | 0.67 |
| 99 | 2 | 25 | 161 | 340 | 100 | 2 | 2019-07-23 | T15 | 1.08 | 0.77 |
| 100 | 2 | 22 | 166 | 330 | 100 | 1 | 2019-07-23 | T16 | 1.13 | 0.69 |
| 101 | 2 | 25 | 160 | 340 | 100 | 2 | 2019-07-23 | T17 | 1.12 | 0.83 |
| 102 | 2 | 22 | 164 | 330 | 100 | 1 | 2019-07-23 | T18 | 1.13 | 0.68 |
| 103 | 2 | 25 | 160 | 340 | 100 | 2 | 2019-07-23 | T19 | 1.05 | 0.78 |
| 104 | 2 | 22 | 167 | 330 | 100 | 1 | 2019-07-23 | T20 | 1.13 | 0.73 |
| 105 | 2 | 25 | 161 | 340 | 100 | 2 | 2019-07-23 | T21 | 1.07 | 0.81 |
| 106 | 2 | 22 | 165 | 330 | 100 | 1 | 2019-07-23 | T22 | 1.12 | 0.7 |
| 107 | 2 | 25 | 156 | 340 | 100 | 2 | 2019-07-23 | T23 | 1.04 | 0.83 |
| 108 | 2 | 22 | 167 | 330 | 100 | 1 | 2019-07-23 | T24 | 1.09 | 0.65 |
| 109 | 2 | 25 | 162 | 340 | 100 | 2 | 2019-07-23 | T25 | 1.08 | 0.77 |
| 110 | 2 | 22 | 168 | 330 | 100 | 1 | 2019-07-23 | T26 | 1.17 | 0.72 |
| 111 | 2 | 25 | 160 | 340 | 100 | 2 | 2019-07-23 | T27 | 1.1 | 0.86 |
| 112 | 2 | 22 | 160 | 330 | 100 | 1 | 2019-07-23 | T28 | 1.2 | 0.74 |
| 113 | 2 | 22 | 171 | 330 | 100 | 1 | 2019-07-23 | T29 | 1.2 | 0.73 |
| 114 | 2 | 22 | 175 | 330 | 100 | 3 | 2019-07-23 | T30 | 1.22 | 0.64 |
| 115 | 2 | 20 | 167 | 335 | 125 | 7 | 2019-07-23 | T31 | 1.09 | 0.84 |
| 116 | 2 | 22 | 168 | 330 | 100 | 1 | 2019-07-23 | T32 | 1.2 | 0.67 |
| 117 | 2 | 22 | 177 | 330 | 100 | 1 | 2019-07-24 | T01 | 0.89 | 0.8 |
| 118 | 2 | 22 | 178 | 330 | 100 | 1 | 2019-07-24 | T02 | 0.99 | 0.79 |
| 119 | 2 | 22 | 177 | 330 | 100 | 1 | 2019-07-24 | T03 | 0.9 | 0.82 |
| 120 | 2 | 22 | 177 | 330 | 100 | 1 | 2019-07-24 | T04 | 0.88 | 0.83 |
| 121 | 2 | 22 | 177 | 330 | 100 | 1 | 2019-07-24 | T05 | 0.91 | 0.77 |
| 122 | 4 | 20 | 171 | 362 | 110 | 4 | 2019-07-24 | T06 | 0.89 | 0.89 |
| 123 | 4 | 22 | 169 | 330 | 100 | 1 | 2019-07-24 | T07 | 0.88 | 0.86 |
| 124 | 4 | 20 | 163 | 362 | 110 | 4 | 2019-07-24 | T08 | 0.9 | 0.99 |
| 125 | 4 | 22 | 168 | 330 | 100 | 1 | 2019-07-24 | T09 | 0.91 | 0.76 |
| 126 | 4 | 20 | 169 | 362 | 110 | 4 | 2019-07-24 | T10 | 0.92 | 0.95 |
| 127 | 4 | 22 | 170 | 330 | 100 | 1 | 2019-07-24 | T11 | 0.85 | 0.89 |
| 128 | 4 | 20 | 165 | 362 | 110 | 4 | 2019-07-24 | T12 | 0.87 | 0.96 |
| 129 | 4 | 22 | 170 | 330 | 100 | 1 | 2019-07-24 | T13 | 0.98 | 0.79 |
| 130 | 4 | 20 | 168 | 362 | 110 | 4 | 2019-07-24 | T14 | 0.85 | 0.99 |
| 131 | 4 | 22 | 167 | 330 | 100 | 1 | 2019-07-24 | T15 | 0.89 | 0.81 |
| 132 | 4 | 20 | 165 | 362 | 110 | 4 | 2019-07-24 | T16 | 0.87 | 0.99 |
| 133 | 4 | 22 | 170 | 330 | 100 | 1 | 2019-07-24 | T17 | 0.93 | 0.8 |
| 134 | 4 | 20 | 164 | 362 | 110 | 4 | 2019-07-24 | T18 | 0.84 | 0.96 |
| 135 | 4 | 22 | 167 | 330 | 100 | 1 | 2019-07-24 | T19 | 0.93 | 0.79 |
| 136 | 4 | 22 | 168 | 330 | 100 | 1 | 2019-07-24 | T21 | 0.93 | 0.82 |
| 137 | 4 | 20 | 165 | 362 | 110 | 4 | 2019-07-24 | T22 | 0.91 | 1.09 |
| 138 | 4 | 22 | 168 | 330 | 100 | 1 | 2019-07-24 | T23 | 0.92 | 0.84 |
| 139 | 4 | 20 | 164 | 362 | 110 | 4 | 2019-07-24 | T24 | 0.96 | 0.96 |
| 140 | 4 | 22 | 170 | 330 | 100 | 1 | 2019-07-24 | T25 | 0.91 | 0.8 |
| 141 | 2 | 20 | 170 | 362 | 110 | 4 | 2019-07-25 | T01 | 0.86 | 0.88 |
| 142 | 2 | 22 | 172 | 330 | 100 | 1 | 2019-07-25 | T02 | 0.93 | 0.78 |
| 143 | 2 | 20 | 168 | 362 | 110 | 4 | 2019-07-25 | T03 | 0.9 | 0.95 |
| 144 | 2 | 22 | 170 | 330 | 100 | 1 | 2019-07-25 | T04 | 1.03 | 0.7 |
| 145 | 2 | 20 | 167 | 362 | 110 | 4 | 2019-07-25 | T05 | 0.89 | 0.93 |
| 146 | 2 | 22 | 168 | 330 | 100 | 1 | 2019-07-25 | T06 | 1.08 | 0.64 |
| 147 | 2 | 20 | 163 | 362 | 110 | 4 | 2019-07-25 | T07 | 0.9 | 0.95 |
| 148 | 2 | 22 | 168 | 330 | 100 | 1 | 2019-07-25 | T08 | 1.05 | 0.63 |
| 149 | 2 | 20 | 169 | 362 | 110 | 4 | 2019-07-25 | T09 | 0.89 | 0.93 |
| 150 | 2 | 22 | 168 | 330 | 100 | 1 | 2019-07-25 | T10 | 1.06 | 0.64 |
| 151 | 2 | 22 | 173 | 330 | 100 | 1 | 2019-07-25 | T11 | 1.12 | 0.6 |
| 152 | 2 | 22 | 175 | 330 | 100 | 1 | 2019-07-25 | T12 | 1.12 | 0.63 |
| 153 | 2 | 22 | 175 | 330 | 100 | 1 | 2019-07-25 | T13 | 0.93 | 0.81 |
| 154 | 2 | 22 | 173 | 330 | 100 | 1 | 2019-07-25 | T14 | 0.83 | 0.86 |
| 155 | 2 | 25 | 169 | 340 | 100 | 2 | 2019-07-25 | T15 | 0.84 | 0.95 |
| 156 | 2 | 22 | 170 | 330 | 100 | 1 | 2019-07-25 | T16 | 0.83 | 0.8 |
| 157 | 2 | 25 | 167 | 340 | 100 | 2 | 2019-07-25 | T17 | 0.78 | 1 |
| 158 | 2 | 22 | 170 | 330 | 100 | 1 | 2019-07-25 | T18 | 0.91 | 0.78 |
| 159 | 2 | 25 | 166 | 340 | 100 | 2 | 2019-07-25 | T19 | 0.81 | 0.93 |
| 160 | 2 | 22 | 178 | 330 | 100 | 1 | 2019-07-25 | T20 | 0.97 | 0.83 |
| 161 | 2 | 25 | 172 | 340 | 100 | 2 | 2019-07-25 | T21 | 0.77 | 0.94 |
| 162 | 2 | 22 | 172 | 330 | 100 | 1 | 2019-07-25 | T22 | 0.94 | 0.81 |